Hybrid power supply system of a selected residential building based on innovative renewable sources

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Abstract

The growth in the demand for energy knows no end. Yet there is pressure more than ever before to meet this growing demand in the cleanest possible ways. This creates an attractive opportunity especially in countries still dealing with energy poverty like Nigeria to fill the energy gap with energy from clean sources. This thesis evaluates the potential for hybrid power systems comprising of renewable sources to meet the electrical load requirement of a selected residential building at the lowest possible cost. The building is located in Warri, Nigeria where power supply is still largely unreliable and very dependent on fossil sources. The hybrid power systems studied in this thesis combine various scenarios of wind turbine, photovoltaic array, gasoline generator, and fuel cell to produce electricity. Energy storage is applied as well. These systems are designed and simulated with HOMER Pro which is a software for optimizing microgrid design for residential, industrial, and commercial applications. HOMER Pro ran several simulations to obtain the optimal sizes of the components of the various scenarios that satisfy the electrical load requirements at the lowest net present cost. A base scenario comprising solely of a gasoline generator is simulated as well for the purpose of comparison. HOMER Pro also calculated the net emission from these systems. The results suggest that hybrid power systems offer cost and emission benefits when compared to the base scenario. After the studied systems were evaluated, a wining scenario was selected for the building.

Keywords: Hybrid power systems, load, solar, storage, wind, simulation

Resumo

O crescimento do consumo de energia parece não abranda. No entanto, é prementa responder ao consumo crescente da maneira mais limpa possível. Isso cria uma oportunidade atraente, especialmente em países que ainda lidam com a pobreza energética, como a Nigéria, para preencher a lacuna energética com energia de fontes limpas. Os sistemas de energia híbridos, especialmente aqueles compostos por fontes de energia renováveis, são tecnologias confiáveis de forma a garantirem que as os consumos de energia elétrica sejam satisfeitos de maneira limpa e económica. Esta dissertação avalia o potencial de sistemas híbridos de energia compostos por fontes renováveis para atender aos requisitos de carga elétrica de um edifício residencial com o menor custo possível. O edifício está localizado em Warri, Nigéria, onde o fornecimento de energia ainda não é fiável e depende muito de fontes fósseis. Os sistemas híbridos de energia estudados nesta dissertação combinam vários cenários a partir de energia eólica, sistema fotovoltaico, gerador a gasolina e célula a combustível para produzir eletricidade. O armazenamento de energia também é contemplado. Esses sistemas são projetados e simulados com o HOMER Pro, que é um software para otimizar o projeto de micro redes para aplicações residenciais, industriais e comerciais. Um cenário básico compreendendo apenas um gerador a gasolina também é simulado para fins de comparação. Os resultados sugerem que os sistemas de energia híbridos oferecem benefícios de custo e emissão quando comparados ao cenário base.

Palavras-chave: Sistemas de energia híbridos, carga, fotovoltaico, armazenamento, eólica, simulação

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List of acronyms

AD	Anaerobic digestion
CAES	Compressed air energy storage
CC	Cycle charging
CHP	Combined heat and power
EGS	Enhanced geothermal systems
FC	Fuel cell
FLA	Flooded lead acid battery
HDR	Hot dry rock
HPS	Hybrid power systems
HRES	Hybrid renewable energy systems
LA	Lead acid battery
LF	Load following
LHS	Latent heat storage
LPSP	Loss of power supply probability
NPC	Net present cost
O&M	Operation and maintenance cost
PCM	Phase change material
PHES	Pumped hydro energy storage

PV	Photovoltaic
SHS	Sensible heat storage
TCS	Thermochemical storage
TES	Thermal energy storage
VRB	Vanadium-Redox Flow Battery
VRLA	Valve-regulated lead acid battery
WT	Wind turbine

Chapter 1. Introduction

For over a century the tradition of burning coal, oil and gas has made it possible for humanity to achieve high standards of living through many outstanding innovations in the world of energy science and technology, yet in recent decades, the need for a global shift from fossil driven systems of energy production and consumption to clean and sustainable driven systems have been heightened. A major catalyst for this transition is the impact of greenhouse emissions from these systems. Combusting fossil fuel to produce energy has been named as one of the major causes of increased atmospheric carbon dioxide [9]. Atmospheric carbon dioxide has been increasing at an alarming rate. Over the last 60 years the increase is about 100 times more than the increase in the previous years from natural causes. These emissions have been linked to climate change, air pollution and respiratory diseases [2]. At the same time the world energy demand is also on the increase. It is expected to grow by nearly 50% from 2018 to 2050 [4]. Although this increased demand reflects across all major sectors of the economy, it is pertinent to note that industry and buildings alone accounts for about 75 percent of the growth in energy demand [3]. According to British Petroleum’s energy outlook 2020 Edition, most of this growth will come from emerging economies largely due to increasing population, prosperity, and increased access to electricity.

Nigeria is an emerging economy with an estimated population of 200 million people. According to the world bank, about 43 percent of its population still lacks access to electricity, and those who have access, suffer from erratic supply. This is why off-grid power generation is commonplace in Nigeria. Most residential buildings have diesel or gasoline generating sets. These generators cost a lot more to operate and maintain, create excruciating noise pollution, and emit tons of greenhouse gases to the atmosphere [6]. Various studies have been carried out on off grid renewable energy solutions. Promising renewable energy technologies include wind, solar, geothermal, biomass and hybrid systems of two or more technologies to meet the energy demands of residential buildings.

Hybrid power systems (HPS) combine more than one generating unit to meet the load requirement [5]. HPS can exist as standalone systems or grid connected. HPS can also be classified as Stand-alone systems are installed with storage devices to satisfy load requirements while grid-connected systems can feed excess generation to the grid or acquire supply from the grid in times of deficiency [7]. In recent times, HPS consisting solely of renewable energy sources is gaining more application, due to higher efficiency and lower net present cost. An added advantage of HPS comprising solely of renewable sources is that at times when one renewable source is not in abundance and cannot supply the needed power, the other can complement for it.

Asides the benefits of sustainability, quietness, and cost effectiveness, hybrid power supply systems for residential buildings offer a viable alternative to achieving the desired full nationwide electrification in Nigeria. In this thesis several hybrid power systems are analyzed for a selected residential building to select a system that meets the load requirement at the least possible net present cost.

This thesis is structured as follows: Chapter 2 discusses the basic concepts of hybrid power systems and renewable energy sources that can be utilized in designing and installing hybrid systems. chapter 3 discusses the concept of energy storage. The methodology applied in this study is described in chapter 4. Chapter 5 presents and discusses the obtained results. The main conclusions are drawn in chapter 6.

Chapter 2. Hybrid power systems

Hybrid power systems are power generating systems consisting of more than one source of energy [6]. When the sources of energy are all renewable, it is sometimes referred to as hybrid renewable energy systems (HRES) [69]. Renewable energy sources are unpredictable, and this creates a problem in using one renewable resource to meet changing demand. To overcome this drawback, more than one renewable energy source can be combined to boost reliability, reduce cost, and avoid LPSP. HPS can be categorized as grid-connected and standalone systems. Fig 2.1 illustrates a hybrid power system configuration of a residential building.

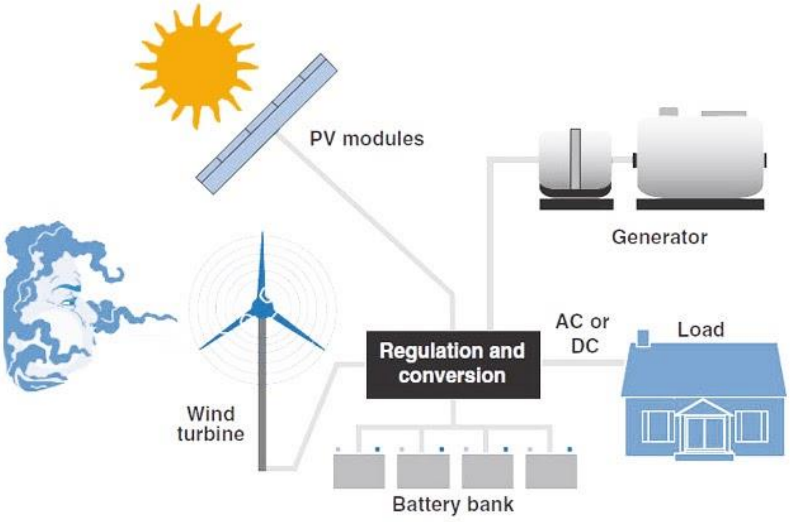


Fig 2.1 Hybrid Power system of a residential building [https://sainilossolar.com/hybrid]

2.1. Grid-connected systems

A grid connected HPS by design allows renewable generating unit to serve the electric demand during those periods (seasonal or daily) when the renewable resources are abundant and rely on the grid to meet the load demand when these resources are not available [70]. Additionally, when excess electricity is generated, it can be fed back into the grid. Grid connected HPS eliminates the requirement for storage devices.

2.2. Standalone systems

Standalone HPS systems as the name implies operate independently of the grid. Due to the intermittent and unpredictable nature of renewable energy resources coupled with the fact that the electric demand changes with time, standalone HPS may struggle to always meet electric demand. As way of mitigating this uncertainty, energy storage devices like batteries, are installed alongside these systems [18].

2.3. Renewable energy sources

Solar photovoltaic systems:

Solar photovoltaic systems convert solar energy to heat or electricity [15]. A simple PV system is made up of one or several solar panels to absorb and convert the solar energy, an inverter to convert the solar output from DC to AC and other accessories that facilitate its proper working. Solar panels are made of semiconductors. Silicon is the semiconductor most used. A PV cell simply is a thin wafer composed of a very thin layer of phosphorus-doped (N-type) silicon layered on top of a thick layer of boron-doped (P-type silicon). The structure (atomic or crystalline) and electron configuration of the semiconductors allows light energy to be absorbed and an electrical field is created near the top of the cell surface [72]. The silicon atoms hold the surrounding electrons. Some of these electrons are less firmly held than others and an appropriate strike of light energy from the sun can knock them off, freeing these electrons. The free electrons then flow around a circuit creating an electric current. Because light and not the heat energy is responsible for generating electricity in this manner PV systems can work in both cold and hot locations provided there is sufficient sunlight [33]. However, the PV output will be affected by weather conditions. On a cloudy day for example, the PV output can drop by 10 percent to 25 percent, depending on how often the clouds pass over the PV system. Regardless of the PV cell size a standard PV cell produces around 0.5 ~ 0.6 V in open-circuit condition. The properties that influence the performance and design of PV cells include doping atom concentration (ND donors, NA acceptors), refractive index of the PV cell surface, absorption coefficient, length of diffusion, mobility coefficient and diffusion coefficient of charge carriers resulting from drift and diffusion, lifetime, and band gap energy [19]. To generate higher power, several PV cells can be connected in series and parallel circuits. This is referred to as a solar array [20]. A solar array installed at Malakal Upper Nile State in South Sudan is shown in Fig 2.2.

Fig 2.2 700 kWp Solar photovoltaic system in Malakal, Upper Nile State in South Sudan. [https://www.afrik21.africa]

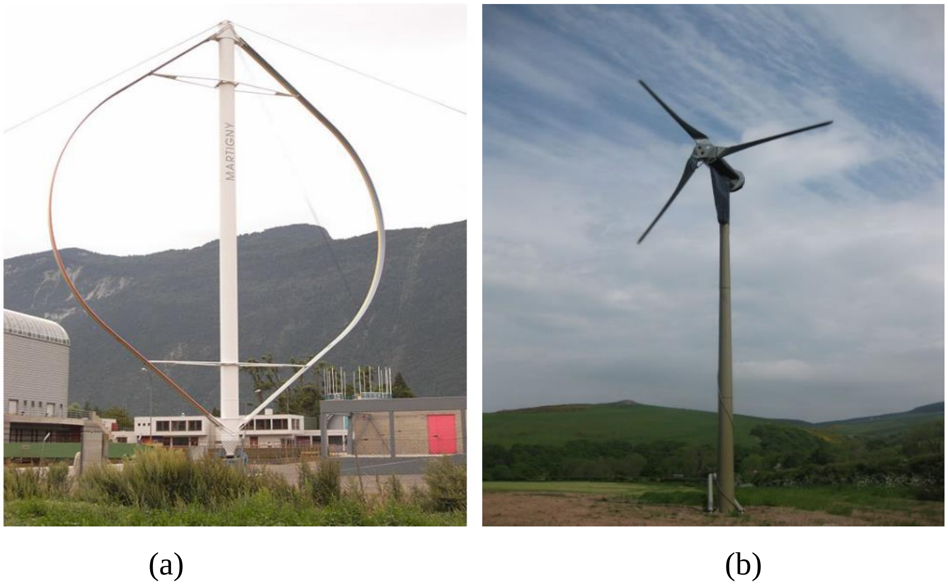
There are two major types of PV cells: crystalline silicon-based and thin-film PV cells. Research is also exploring a mixture of these two types.

- Crystalline Silicon Cells: This type of PV cells are made of crystalline silicon (c-Si) wafers as the semiconductor. Monocrystalline panels are made from single crystals (mono-Si), while polycrystalline panels are made from multiple crystals (multi-Si or poly c-Si) [33]. Monocrystalline cells are peculiar in appearance and sometimes are colored. Because monocrystalline cells are made up of a single crystal, the electrons responsible for generating an electric flow can move more freely. As a result, the monocrystalline panels possess greater efficiency than the polycrystalline panels. In contrast polycrystalline panels due to less freedom electrons have lower efficiency [21]. The advantage of polycrystalline panels over monocrystalline panels is their price tag. They are less expensive than their monocrystalline counterparts.
- Thin Film PV Cells: Thin-film PV cells are a lot thinner than crystalline PV cells. They are composed of amorphous silicon (a-Si). The silicon atoms are arranged randomly in contrast to an orderly arranged structure in the crystalline cells. Thin-film can be made from materials like copper indium gallium selenide (CIGS), cadmium-telluride (Cd-Te) as well as other organic PV materials. Thin film PV cells are generally less efficient than crystalline. Crystalline PV cells have efficiency in the range 15%-21%. While thin film PV cells have efficiency of about 7% [73].
- Third Generation PV Cells: Newer PV cell technologies combine some features of crystalline silicon and thin-film PV cells to improve efficiency. Although many of them are still in their developmental or research stage. Materials used to produce such cells include organic polymers, amorphous silicon. They also possess multiple junctions made up of layers of several semiconducting materials [74].

They are designed primarily to be more practical, efficient, and cost less. Examples include biohybrid solar cells, cadmium telluride solar cells, and concentrated solar cells.

Wind energy systems:

Wind energy harnesses energy from the wind to generate electricity. Wind Turbines convert kinetic energy to mechanical energy [22]. Turbines have propeller-like blades that rotate around a rotor. The rotor turns the drive shaft. The shaft then turns an electric generator. Wind turbines can be horizontal-axis or vertical-axis. Fig 2.3 a, b depicts a horizontal-axis and a vertical axis wind turbine. Horizontal axis wind turbines are more popular. Here the blades rotate along a horizontal axis or parallel with the ground. The advantage of horizontal-axis wind turbines over vertical axis-wind turbines is that they produce more electricity from a given amount of wind. Hence its popularity for harnessing the maximum amount of electricity [33]. However, they are heavier and do not perform very well in turbulent winds. Vertical axis wind turbines: Here the blades rotate along a vertical axis or perpendicular to the ground. Vertical axis turbines can harness wind coming from all directions hence they are sometimes considered the ideal choice of wind turbine. They however perform poorly in places that lack a consistent wind. Additionally, due to public perception the turbines cannot be placed high enough where they can be powered by steady wind. The amount of energy generated by a wind turbine is dependent on some factors that include size of wind turbines, length of blades, air density, wind speed, air density, and swept area [24].



(a) (b)

Fig 2.3 a, b Vertical and Horizontal axis wind turbine [Wikimedia Commons author (GNU free documentation license)]

There are two categories of wind turbine power plants: standalone and wind farms power plants.

- Standalone Wind Turbine Power Plant: Application of this category of wind turbine power plants is most found in buildings unconnected to the grid or buildings with unreliable power supply. Other applications include battery charging, water heating or cooling, water pumping etc. Standalone wind turbines that can power single residential buildings can generate about 10 kilowatts (kW) of electricity. Some of the largest wind turbines currently in use for industrial and agricultural applications can generate up to 100 kW [25].
- Wind farm Power Plants: When large turbines are grouped together to produce power, they are referred to as wind farms. It is common practice to supply the produced electricity to the grid. Hence, they are also referred to as grid-connected wind turbine power plants. Grid connected wind turbine power plants allow excess electricity to be sold to the global network. It also allows electricity to be purchased when the wind turbine cannot generate the needed power [23].

Biomass systems

Biomass refers to materials made up of plants and animal material. This includes their wastes and residues [26]. Biomass energy is derived through the process of photosynthesis. Photosynthesis is a process utilized by plants to convert sunlight energy to chemical energy. The major product of this process is carbohydrate (starch or sugar) which stores energy synthesized from carbon dioxide and water molecules [27]. The photosynthetic reaction is as follows [57].

$$6CO_2 + 6H_2O + \text{Light energy} \rightarrow C_6H_{12}O_6 + 6O_2 \qquad (2.1)$$

Biomass feedstock can vary widely. Depending on the source, feedstock can be categorized into agricultural/forest and food/industrial waste. Wood, agricultural waste, vegetable oils, sugar cane etc. are some examples of Biomass resources utilized generating energy. Biomass energy can be utilized using any of the following technologies: Thermochemical process, Biochemical process, mechanical extraction [28].

Thermochemical process: This employs processes such as direct combustion, gasification, liquefaction, and pyrolysis to convert biomass resources to fuel products [27]. Direct combustion process is perhaps the simplest and most popular technology to utilize biomass energy. However, the downside to this method is that the biomass resource often has low thermal energy contents. As a result, combustion of biomass is a less efficient process than fossil fuel combustion. Electricity can be produced from combustion of biomass of any source, but practically, it is feasible for resources with less than 50 percent moisture content. Usually, biomass feedstock is pre heated to dry before use to reduce the moisture content. The heat from combustion can produce steam that drives a turbine to generate electricity. Combustion systems can range from a few kilowatts to a few gigawatts of thermal units depending on the application. Biomass combustion reaction is shown in below [58].

$$\text{Biofuel} + O_2 \rightarrow CO_2 + H_2O + \text{heat} \qquad (2.2)$$

$$\text{Biofuel} + \text{Air} \rightarrow CO_2 + H_2O + N_2 + \text{heat} \qquad (2.3)$$

Pyrolysis is a thermochemical process that involves heating biomass resources in the absence of oxygen [35]. The absence of oxygen causes the feedstock to thermally decompose rather than combust. Pyrolytic decomposition of biomass can be achieved at medium (300o-800oC) to high temperatures (800o-1300oC) [34]. Generally, the products from this process are liquid, solid and syngas. These products are themselves valuable fuels. They include charcoal, methane, hydrogen, water, carbon monoxide and carbon dioxide

Pyrolytic reactions include [59]:

$$C + 2H_2O \rightarrow 2H_2 + CO_2 \qquad (2.4)$$

$$C + H_2O \rightarrow H_2 + CO \qquad (2.5)$$

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2 \qquad (2.6)$$

$$CH_4 + H_20 \rightarrow CO + 3H_2 \qquad (2.7)$$

Temperature is a very crucial variable in the pyrolysis product yield. Hence pyrolysis is grouped into low temperature pyrolysis where the product is mainly charcoal, moderate temperatures where the main product is liquids and high temperatures where the main product is gases. Pyrolysis can also be classified into slow, fast, and flash pyrolysis based on the residence time. Some publications also classify pyrolysis into catalytic, microwave, vacuum, and hydropyrolysis [36]. In Slow pyrolysis, the residence time is within the range of 10-100min at heating rates of about 0.1-1ºC/s. The residence time and heating rate for fast pyrolysis is 0.5-5s and 10-200ºC/s respectively. For flash pyrolysis the residence time and the heating rates are < 0.5s and >1000ºC/s. The result of these different conditions is different pyrolytic products. To determine which is the best pyrolytic process to undertake will be determined by the desired product. To increase the heating value of biomass, a type of mild pyrolysis is usually carried out. A process often referred to as torrefaction. This process produces torrefied biomass which are very high-quality feedstock for gasification. The result is that they produce high quality syngas. It is described as mild because it is carried out at temperatures ranging from 250–350oC in limited amounts of oxygen [75]. Typically, all moisture is removed. The removal of moisture reduces the weight of the biomass by about 30 percent, but the energy loss is only around 10 percent.

Liquefaction is a thermochemical process that converts biomass to liquid products (bio-oil). The biomass undergoes complicated chemical reactions in a solvent medium [37]. When the reaction medium is water, it is referred to as Hydrothermal liquefaction. Hydrothermal liquefaction can be classified as, hydrothermal carbonization, hydrothermal liquefaction and hydrothermal gasification depending on the temperature of the process. Hydrothermal carbonization occurs at temperatures below 250oC and produces hydrochar. Hydrothermal liquefaction occurs at temperatures of 250oC-375oC and produces biocrude. Hydrothermal gasification occurs at temperatures >375oC and produces syngas. To increase the yield this reaction is often catalyzed [26].

Gasification is a thermochemical process that leads to the production of syngas from biomass resources. Syngas is also referred to as producer gas [30]. The components of the gas include CO_2, CO, N_2, H_2, H_2O and other hydrocarbons like CH_4, C_2H_4, C_2H_6, etc. Depending on the nature of the feedstock, trace amounts of tars, NH_3, H_2S may also be produced. Gasification is carried out at high temperatures (800-900oC) During the gasification process, depending on the nature of the feedstocks and the gasification conditions, the chemical reactions can progress to different extents. First the feedstock undergoes combustion reaction but unlike traditional combustion the amount of oxidant used is reduced to about one-fifth to one-third [33]. The result of this partial oxidation is the production of CO and H_2. A small portion of the carbon is however completely oxidized to CO_2. Based on the medium of partial oxidation, gasification can be classified into oxygen, air, steam gasification or a mixture of any/all the mediums. The quality of gas produced from air gasification is generally poor quality in terms of heating value. The gas produced from oxygen gasification is relatively better in quality [13]. The energy required to drive the endothermic reaction is supplied by heat produced by the partial. Gasification is also applied to produce not only producer gas, but also chemicals like ethylene, methane, fatty acids, adhesives etc [31].

Combustion reaction [30]:

$$C + 1/2O_2 \rightarrow CO \qquad (2.8)$$

$$CO + 1/2O_2 \rightarrow CO_2 \qquad (2.9)$$

$$H_2 + 1/2O_2 \rightarrow H_20 \qquad (2.10)$$

Other reactions:

$$C + H_20 \longleftrightarrow CO + H_2 \qquad (2.11)$$

$$C + CO_2 \longleftrightarrow 2CO \quad (2.12)$$

$$C + 2H_2 \longleftrightarrow CH_4 \quad (2.13)$$

Three major groups of gasifiers are used to carry out the process of gasification. They include fixed bed, fluidized bed, and entrained flow gasifiers [30]. Examples of fixed bed gasifiers are downdraft and updraft gasifiers. Examples of fluidized bed gasifiers are circulated and bubbling fluidized bed gasifiers. In the industry the downdraft fixed bed gasifiers are most widely used [32].

Biological process: The biological process of conversion depends on the biological activities of microorganisms (yeast, bacteria etc) to convert biomass into liquid or gaseous fuel. Two biological processes are well known, Anaerobic digestion (AD) and fermentation.

Fermentation is a process employed to break down sugar to alcohol (ethanol). Generally, the organism which is added to the biomass feeds produces ethanol and CO2. The ethanol is separated from other components of the reaction by the process of distillation and dehydrolyzed. The ethanol can be utilized as fuel or used as an additive. Based on the nature of the biomass resource, fermentation can be grouped into starches, sugars, and cellulose fermentation [76]. Starches can be sourced from yam, potatoes, cassava etc. starches need to be hydrolyzed to sugars before they can undergo fermentation. Sugars are sourced from sugar cane, maple syrups, fruits etc and can be converted directly by adding the fermenting organism to produce ethanol. cellulose is sourced from wood, grasses, plant residues etc. and just like starches need to be converted to sugars before fermenting organisms can act on them. Fermentation reaction [60]:

$$C_6H_{12}O_6 + \text{yeast} \rightarrow 2C_2H_5OH + 2CO_2 + \text{Heat} \quad (2.14)$$

AD is the process of breaking down biodegradable material such as food and animal waste in the absence of oxygen [40]. AD is carried out in an aerobic digester which is typically a large and airtight vessel. The major product of this process is biogas which is rich in methane. Biogas can be used as fuel for cooking, CHP plants etc. The residue after the extraction of biogas is referred to as digestate. The digestate is often composed of both solid and liquid parts that can be separated and treated to serve as biofertilizers or raw materials for production of other bioproducts [77].

Geothermal systems

Thermal energy stored within the earth is referred to as geothermal energy [41]. The hottest part of the earth is situated at about 2,900 km below the earth's surface. Also known as the core. Friction and gravitational forces of the earth are responsible for a small portion of the core's heat. The decay of radioactive isotopes is, however, responsible for most of the core's heat [43]. There are two major forms of heat transfer occurring within the crust: convection and conduction. Conduction is a mode of heat transfer of heat by direct molecular contact. Conduction does not cause displacement of the molecules involved. Convection is a mode of heat transfer from one place to another by means of a mobile fluid. In liquids and gases, the main form of heat transfer is convection. Unlike other renewable energy resources like solar and wind, geothermal energy is very reliable. It is a continuously available resource meaning it can be used to produce heat and electricity throughout the day.

There are four main groups of geothermal resources namely:

- Hydrothermal: Refers to steam or hot water found at depths of about 100m to 4500m. Hydrothermal resources are convective systems and can be used to generate electricity when their temperatures range from 90ºC to 350ºC. More than 60 percent of hydrothermal resources have a temperature range of 150ºC and 200ºC [33]. The best type of hydrothermal resources is dry steam. These resources however are not very common.
- Under high pressure layers: Refers to hot springs. They are produced when underground water is heated either by shallow magma bodies or flowing through hot rocks. Stored at depths of 3000m to 6000m at high pressure in sedimentary rock layers [41]. They are usually composed of large amounts of minerals including methane.
- Hot dry rock (HDR): Refers to thermal energy stored within dry, hot and impermeable crystalline rocks buried deep beneath the Earth [42]. HDR is quite like hydrothermal. While hydrothermal contain hot fluid already in place, HDR are artificial thermal reservoirs created by drilling wells and injecting fluid from the surface under high pressure. The fluid injected under high pressure create cracks. The wells are about 4000m to 5000m deep. Some wells serve as injection wells while others are recovery wells. The hot fluid recovered are used to turn turbines that generate electricity.
- Magma conduits: When underground rock formations are heated to temperatures of 700ºC to 1500˚C, they form magma. Magma resides in the earth's lower crust and mantle but can flow to the earth's surface as lava. Due to how low magma is situated in the earth (3000m-10000m), exploitation of this type of geothermal resource is challenging [41].

Of the four groups, hydrothermal geothermal resources is the most preferred for exploitation owing to economic feasibility. Fig 2.4 shows images of geothermal eruptions in Mount Stromboli, Castle Geyser, Yellowstone National Park, Wyoming, and Volcanoes National Park, Hawaii.

Fig 2.4 Geothermal Eruptions [https://www.nationalgeographic.com]

There are several types of geothermal plants. They include,

- Dry Steam power plants: This type of plants utilize dry steam piped from their hydrothermal stores to fuel turbines for electricity generation. This type of power plant is the oldest type of geothermal power plant, and they generate between 15–20 megawatt of electricity [78].
- Flash-Steam Power Plant: This type of plant uses underground hot water and steam with temperatures of about 180^{o}C. The water is pumped into a separator with low pressure, where it rapidly evaporates (flashes) to steam and then channeled to a turbine to produce electricity [33]. They are of two types: one-stage and two-stage plants. The difference is in the number of separators used. In the one-stage plants the water flows into one separator where steam is produced to fuel the turbine.

  In the two-stage plant, after the production of steam in the first separator, the hot water enters a second separator [80]. Flash-steam power plants are very common, and they can generate about 10-50 megawatts of electricity.
- Binary Cycle Power Plants: In Binary cycle power plants, uses liquid hydrothermal resources (water) with temperatures between 70oC-180oC. The hot water is used to heat a secondary fluid of organic nature (Isobutene or Freon). The steam generated from heating the secondary fluid is used to generate electricity. The water is returned to its source to be reheated [79].
- Enhanced Geothermal Systems: For geothermal resources to be exploited to produce energy it has to be hydrothermal meaning the underground resources must be hot enough, contain fluid and be permeable. Hot but dry resources do not meet this criterion. EGS helps to make these hot dry resources fluid and permeable. This is achieved by drilling, fracturing and injection. Generally, a well is drilled and then water is injected at high pressure to create more cracks. Water is then pumped into the created reservoir which absorbs the heat from the hot rocks. The hot water is then piped to the surface [81]. The hot water can be used to heat a secondary fluid with low boil point. This creates

steam that can be used to generate electricity. It is important to note that this type of activity can lead to chain of seismic activity or small earthquakes.

An example is in Basel, Switzerland, where the injection of water caused some small earthquakes that lead to the shutting down of the project in 2009.

Although geothermal energy is a clean energy source, it is not without drawbacks. Small seismic events have been found to be associated with geothermal drilling and injection activities.

Chapter 3. Storage systems

An important component of HRES are storage systems. Storage ensures uninterrupted power supply. When the renewable energy resource such as wind or photovoltaic is surplus, it meets the required demand while the excess is stored to be used when the renewable energy resource is not sufficient. Storage systems can be classified into mechanical, electrochemical, and thermal storage systems [44].

3.1. Mechanical storage

- Flywheel electric energy storage: Flywheel technology converts electrical energy to mechanical energy by using an electric motor to drive a flywheel which rotates at high speed [82]. When needed the flywheels can drive a generator to produce electricity. The rotational speed of the flywheel reduces when energy is extracted from it and vice versa.
- Compressed Air Energy Storage (CAES): CAES stores energy to be used later in the form of compressed air [83]. CAES plants are similar to pumped-hydro power plants. Just like PHES pumps water from a lower reservoir to an upper reservoir when there is excess power supply, CAES plants compress ambient air as well as other gas and store them under pressure during periods of excess power supply [84]. When needed, the compressed air can be heated and expanded in an expansion turbine that drives a generator to generate electricity. CAES can be of two types: CAES in geological formations such as salt formations, aquifers and CAES in tanks or pipes. CAES plants can store huge amounts of energy. With about 70 bars of pressure, CAES plants can store as much as 50 to 300 MW [47].
- Pumped hydro energy storage (PHES): This method is applied in hydroelectric electric generation to store excess energy. PHES is composed of an upper and lower reservoir. During periods of low demand, water is pumped to the upper reservoir [85]. The water can be pumped by the electricity generated on site or alternatively cheap renewable energy from solar or wind farms. This water is released later during periods of high electricity demand to generate sufficient electricity to meet the demand. An illustration of PHES is shown in Fig 3.1

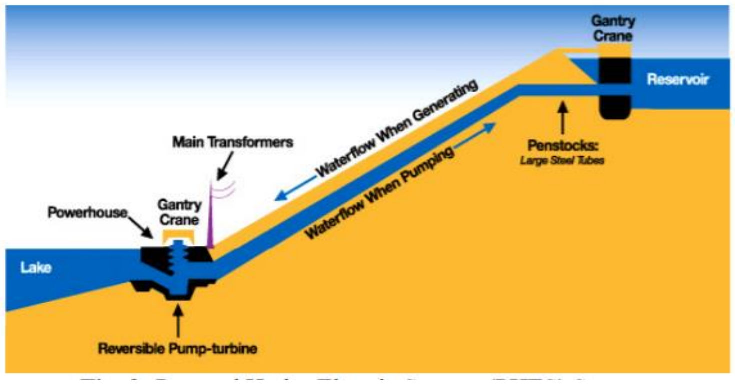


Fig 3.1 Pumped Hydro Electric Storage (PHES) System [84]

PHES is a very attractive storage method because it can provide stability, energy-balancing, and ancillary grid services like control of network frequency. PHES can respond to huge electrical load fluctuations within a few seconds.

3.2. Electrochemical Storage

Electrochemical storage stores electrical energy in chemical form and converts back to electrical energy when needed. This method of storage stems from the fact that the electron is a carrier common to both chemical and electrical energy. A cell is a unit electrochemical device capable of converting chemical energy contained in its active components to electric energy [86]. One or more cells make up a battery. This is done through reversible REDOX reactions. Fig 3.2 shows the simplified diagram of a cell. Batteries can be primary or secondary. Primary batteries cannot be recharged after use, while secondary batteries can be recharged by passing current through the circuit in a direction opposite to direction of current flow when discharging. Batteries are the most widely used technology for energy storage in HPS [49].

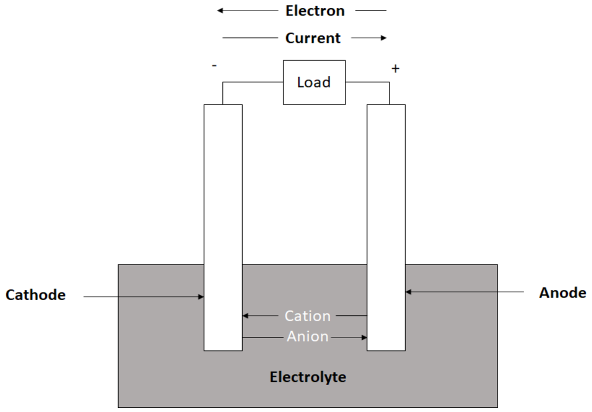


Fig 3.2 An electrochemical cell [www. depts.washington.edu]

Secondary batteries currently being used at commercial scale can be categorized into Standard batteries (Ni-Zn, Ni-Cd, lead-acid), modern batteries (Li–ion, Ni-MH, Li-pol), flow batteries (vanadium redox, Br2-Zn,), special batteries (Ni-H2, Ag-Zn,), and high temperature batteries (Na–metalchloride,Na-S,)

- Lead-acid batteries (LA): The lead-acid battery is composed of a negative and positive electrode immersed in an electrolyte (aqueous solution of H2SO4). The electrodes are made up of a grid and an active mass. Grids are made up of mechanical proof material such as lead alloys [87]. The positive should be corrosion proof, because corrosion lowers the electrical conductivity and leads to mechanical failure of the grid. Both electrodes are separated by a separator to provide electrical insulation, helps to keep the active mass in close contact with the grid and allow free ion migration and electrolyte diffusion. The chemical reaction during discharge is as follows [49]:

  $$PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O \qquad (3.1)$$

  Based on their maintenance operation lead acid batteries are of two types namely, valve-regulated lead acid batteries (VRLA) which require no maintenance and flooded lead acid batteries (FLA) requiring regular maintenance. LA batteries have found the widest application especially in standalone power systems due to the low price and availability of lead, reliability, easy transportation, high voltage of cell (2V), high electrochemical effectivity and extended cycle life [48]. Due to the dual benefit of power parameters and affordability, lead-acid batteries are well suited for medium and large storage applications. However, some of the disadvantages associated with LA are expansion of the positive plate and fractioning of positive active mass, acid stratification, positive grid corrosion and incomplete charging which results in active mass sulphation.
- Nickel-cadmium (Ni-Cd) batteries: Composed of a positive nickel electrode and metallic cadmium as negative electrode. The electrolyte is aqueous KOH (Potassium hydroxide).
  The chemical reaction of discharge is as follows [61]:

  $$2NiOOH + Cd + 2H_2O \rightarrow 2Ni\ (OH)_2 + Cd\ (OH)_2 \qquad (3.2)$$

  Ni-Cd batteries have good specific energy compared to LA batteries. Manufacturing Ni-Cd batteries is relatively easy and they have higher cycle life performance than Lead acid batteries. But since Ni-Cd batteries are several times costlier than lead acid batteries and Cadmium is very toxic, Ni-Cd batteries are not recommended for a wide variety of applications. However, Ni-Cd may be ideal for some applications like engine starting, emergency lighting due to its low maintenance and reliability [88]. There are other batteries that consist of a positive nickel electrode. They include Ni–Zn, Ni-Fe and, Ni-H2. In Nickel-zinc (Ni-Zn) batteries the negative electrode is metallic zinc. The advantages of Ni-Zn over Ni-Cd include less negative impact on the environment and higher energy density (25% higher than nickel-cadmium).

- Nickel-Metal Hydride (Ni-MH) batteries: Here the negative electrode is made up of a metal alloy with hydrogen absorbed in it. They offer greater energy density (25% more) and are more environmentally friendly than the Ni-Cd batteries [89]. However, they have high self-discharge, high pressure build-up that can lead to cell failure and are not as tolerant to overcharge like the Ni-Cd batteries. Some applications of Ni-MH include mobile phones, electric clippers, hybrid electric vehicle, toothbrushes etc.
- Lithium ion (Li-ion) batteries: Here lithium ions move between both electrodes during charging and discharging of the battery one electrode and the other during charge and discharge. The positive electrode is usually a lithium metal oxide, and the negative electrode is made of amorphous carbon or graphite. The electrolyte is made from dissolved lithium salts like $LiBF_4$, $LiClO_4$ and ether. Lithium-ion batteries made up of cobalt oxide positive electrodes ($LiCoO_2$) are the most commercialized of lithium-ion batteries [89]. Others include Lithium iron phosphate ($LiFePO_4$), lithium manganese oxide ($LiMn_2O_4$) and lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$). Li-ion batteries are used mostly for electric vehicles and portable electronics.

The reaction at positive electrode [49]:

$$LiCoO_2 \rightarrow Li1\text{-}xCoO_2 + xLi+ + xe- \qquad (3.3)$$

At negative electrode [49]:

$$xLi+ + xe- + C_6 \rightarrow LixC_6 \qquad (3.4)$$

Some benefits of Li-ion batteries include high energy density, light weight, availability and affordability of carbon. Additionally, carbon is capable of absorbing a fair quantity of lithium and when combined with metal oxides produces a relatively high voltage (3V-4 V). The disadvantages of Li-ion batteries include high cost, overcharging or heating above 100°C which can lead to the decomposition of the positive electrode.

- Ag-Zn battery: The positive electrode is made of a silver active mass formed by sintering silver powder at very high temperatures (400ºC-700ºC) and a silver-plated copper grid. The negative electrode is made up of zinc or a mixture of zinc oxide [62]. The electrolyte is aqueous KOH. The most important part of the Ag-Zn battery is the separator because It prevents short circuit between the electrodes, it prevents silver migration to the zinc electrode preserving the integrity of the zinc electrode. Low ion resistance, thermal and chemical stability in KOH solution are also characteristics the separator must have. The separator is usually made of polypropylene, cellophane, and synthetic nylon [51].

The chemical reaction discharge [62]:

$$Ag_2O_2 + 2H_2O + 2Zn \rightarrow 2Ag + 2Zn\,(OH)_2 \qquad (3.5)$$

zinc-silver oxide batteries are well Known to be the highest energy density. With energy densities about six times more than that of Ni-Cd batteries. However, the major drawbacks are its high cost and poor cycle life. Ag-Zn batteries are used in space satellites, aircrafts, submarines, and other military applications.

- Flow batteries: Also known as vanadium-Redox Flow Battery (VRB) stores energy in electrolyte solutions (containing one or more dissolved ions) in two separate tanks. Fluids in both tanks referred to as catholyte and anolyte are circulated into a stack with electrodes with the use of pumps. The electrodes are separated by a membrane that permits exchange between the catholyte and anolyte [51]. The major difference between flow batteries and traditional batteries is where the energy is stored (electrolyte for flow batteries and electrode for traditional batteries). In flow batteries, the energy capacity is dependent on the volume of the electrolyte while the power is dependent on the surface area of the electrodes. Types of flow batteries include redox, hybrid and membraneless. Some of the benefits of flow batteries include higher energy densities, modularity (meaning they can be modified easily to meet the needed energy capacity either by using bigger tanks or combining multiple tanks), good discharging (they can be completely discharged without affecting capacity negatively), unlimited longevity and safety (they are non-flammable). Some of the disadvantages include high toxicity as a result of the vanadium oxides, huge size and weight. Flow batteries are ideal for large energy storage systems because they are easily scalable.
- Na-S batteries: is an example of a high temperature battery with operating temperatures of 300ºC to 350°C The positive electrode is molten sulfur. The negative electrode is molten sodium, and just like lithium, has its advantages. Sodium is cheap and easily available. Additionally, it has low atomic weight and high reduction potential. Sulfur is also very available in nature and cheap. The electrolyte, unlike conventional batteries, is a solid beta-alumina cylinder. Beta-alumina is an insulator that has high ionic conductivity for sodium ions at temperatures higher than 300ºC. Ions migrate from the sodium electrode to the sulfur electrode forming sodium polysulfides. The chemical reaction during discharge is [63]:

$$2\,Na + 4\,S \rightarrow Na_2S_4 \qquad (3.6)$$

The sodium level drops with discharge and increases during charging. The charging and discharging phases produce enough heat to maintain the operating temperatures of the battery.
Na-S batteries have high energy density, high discharge/ charge efficiency, long cycle life, and are made from available and inexpensive materials. Hence, they are very suitable for stationary energy storage applications [90]. They are more economical with increasing size. There are safety concerns about the Na-S battery because uncontrolled chemical reactions within the cell resulting from fracture of the electrolyte cylinder can lead to fire and corrosion. This can destroy the cell. As a precaution a safety liner can be inserted into the electrolyte to allow the normal sodium flow to the inner wall of the electrolyte and prevent flow in the occasion of a cylinder fracture.

3.3. Thermal storage

Thermal energy storage (TES) stores energy by heating or cooling several mediums [52]. This stored energy can later be used for different types of applications or for generating power. There are three major thermal storage technologies, Latent heat, sensible heat and thermochemical storage. These technologies store energy in a wide range of temperatures (from -40^{o}C to 400^{o}C).

- Sensible heat storage (SHS): Sensible heat storage is simply based on heating or cooling a storage medium which could be solid or liquid. Water is the most employed medium, which is cheap and easily available. Concrete, polymers, stones examples of other materials that can be used. SHS is cost effective and environmentally friendly. SHS has storage efficiency of 50 to 90 percent [54]. The disadvantage of SHS is its low energy density. However, the low cost of SHS is a tradeoff for the density. Additionally, SHS systems can be optimized to improve efficiency by introducing modifications for example water storage systems can be optimized by stratifying the storage tank.
- Latent heat storage (LHS): employs storage in phase change materials. Phase change materials PCMs are basically salts that change phases (liquid to solid or vice versa) at high temperatures. During the phase change they can release and store great magnitudes of energy. LHS can store as much as 100 kWh/m^3, about four times the capacity of SHS [53]. The fundamental edge of using latent heat storage over sensible sensible heat storage is their ability to store heat at a very close temperature range.
- Thermochemical storage (TCS): TCS utilizes a reversible thermochemical process like adsorption to store heat or cold. Efficiency of TCS systems varies between 75 to 100 percent. TCS also offers higher storage capacity than LHS and SHS. TCS can store as much as 300 kWh/m3 [91]. Some of the barriers associated with TCS systems are high cost, corrosion, poor mass and heat transfer. These systems are still in their developmental stages and more need to be done to overcome these challenges. Industrial heating cooling, space cooling TCS are some of the applications of TCS.

3.4. Hydrogen storage

Hydrogen energy storage is a process of storing excess energy in hydrogen form. The hydrogen is produced through electrolysis. Hydrogen is stored either in liquid or gaseous tanks. Hydrogen possesses the highest energy per mass and unlike other storage technologies can store energy for very long periods [92]. As a fuel it has very high potential. However, hydrogen technology is still very costly and has low density at ambient temperature. More still needs to be done to improve the technology in these areas. The hydrogen produced from the electrolysis process can power fuel cells for electricity generation, serve as fuel for engines, and be utilized to reduce carbon intensity by injection into natural gas etc. The device utilizing the electrolysis process to produce electricity is called an electrolyzer. It is made of a cathode, an anode, and a membrane. Depending on the type of membrane and electrolyte in use they could be grouped into proton exchange membrane (PEM), alkaline, and solid oxide electrolyzer [94]. A fuel cell is an electrochemical device that converts the energy of hydrogen directly to electricity [55]. In a fuel cell, the opposite of electrolysis occurs. Hydrogen and oxygen are combined in the fuel cell to generate electricity [64]. The fuel cell is made up of an anode and a cathode separated by an electrolyte membrane. The electrodes also contain catalysts. Fig 3.3 shows a fuel cell diagram. In a fuel cell hydrogen is passed through the anode where the hydrogen atoms are split into protons and electrons while oxygen is passed through the cathode. The proton coming from the anode are passed through the membrane to the cathode, while the electrons flow through a circuit to the cathode and generates electricity and heat.

The product of the reaction at the cathode is water [33].

$$H_2 + 0.5O_2 \rightarrow H_2O \tag{3.7}$$

Fuel cell technology is very promising because it is clean, reliable, and efficient. Additionally, they do not require charging. Fuel cells continue to produce energy if the hydrogen fuel is available. Based on the type of electrolyte used fuel cells can be of several types. They include:

- Proton Exchange Membrane Fuel Cell (PEMFCs) are sometimes referred to as polymer electrolyte membrane fuel cells because they utilize a solid polymer as the electrolyte. In PEMFCs the electrodes are porous carbon containing a platinum catalyst. PEMFCs offer several benefits including high power density and relatively lower weight. Additionally, they can operate at relatively low temperatures (80°C) meaning they require less warm up time [93]. This is why they are known to be very durable cells. The disadvantages of PEMFCs stems from the high cost associated with use of platinum as a catalyst and procedures in place to prevent platinum poisoning by carbon monoxide. PEM fuel cells are widely used in transportation applications (cars, trucks etc).

- Phosphoric acid fuel cells (PAFCs): in PAFCs, the electrolyte in use is liquid phosphoric acid. They are the oldest types of fuel cells. They are majorly used for stationary electricity generation. They perform far better when used for cogeneration with efficiencies over 80 percent rather than standalone generating plants with efficiencies of 35 to 45 percent. PAFCs are more resistant to poisoning than PEM cells [33].

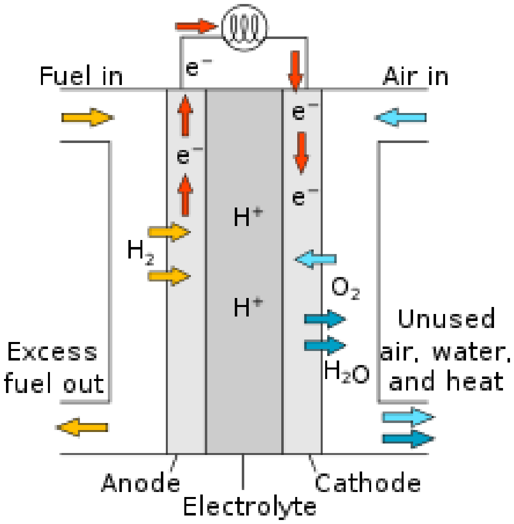


Fig 3.3 Fuel cell diagram [95]

However, PAFCs have relatively lesser power density and as result are weightier and will occupy more space than their counterparts. They are also expensive as the size usually requires more catalyst loading than other fuel cells. Other types include Solid oxide fuel cells (SOFCs), Molten carbonate fuel cells (MCFCs), Reversible fuel cells Alkaline Fuel Cells (AFC).

Chapter 4. Methodology

In this study, some hybrid power systems are modeled. The systems comprise of wind, gasoline generating set, photovoltaic, fuel cell and batteries. The systems utilize different combination of all the above-mentioned components to meet the electric load of a residential building. The models are designed and simulated in HOMER Pro microgrid software by HOMER Energy. HOMER (Hybrid Optimization of Multiple Electric Renewables) Pro is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to help in designing of micropower systems for residential, community, commercial and industrial applications [64]. The tasks performed in HOMER are design, simulation, and optimization.

4.1. Model designing

The design is accomplished by selecting from the HOMER Pro library, the proposed resources (solar, wind, hydro), components (PV panels, wind turbine, generating sets) and specifying the load (heat, electricity, hydrogen). The elements required to design a power system are shown in Fig 4.1. In this study, five scenarios are considered. Homer Pro will tabulate the most optimal sizes of the components of each scenario that meets the electric load by comparing the economics, energy balance and emissions. Fig 4.2 depicts the schematic of the different hybrid systems studied within the context of this thesis.

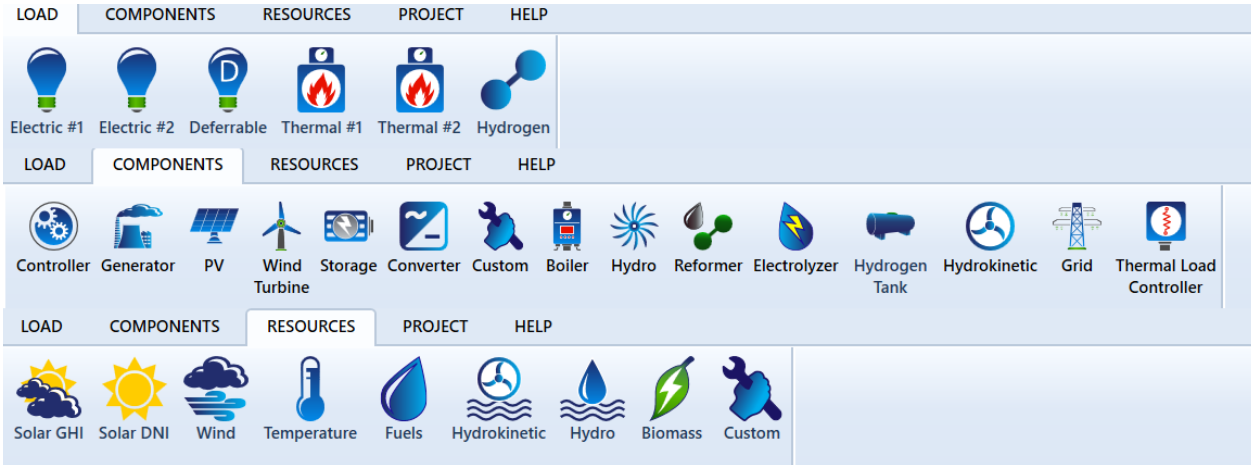
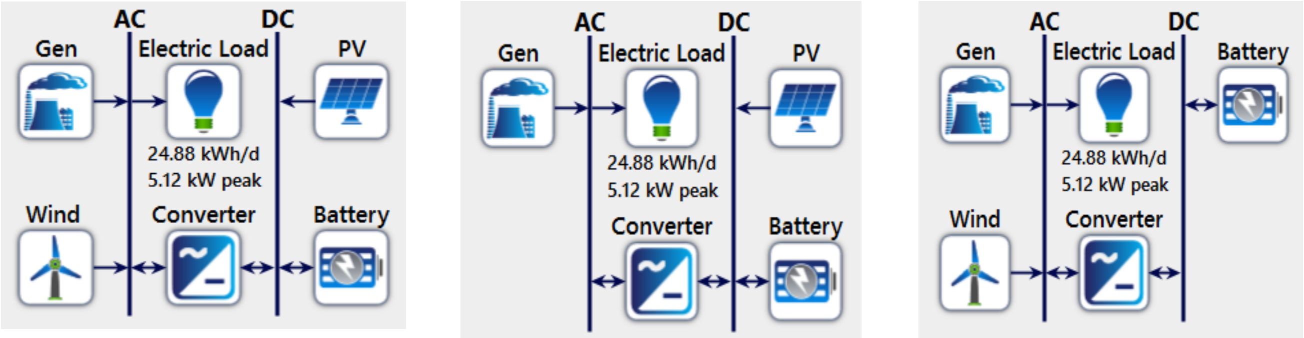
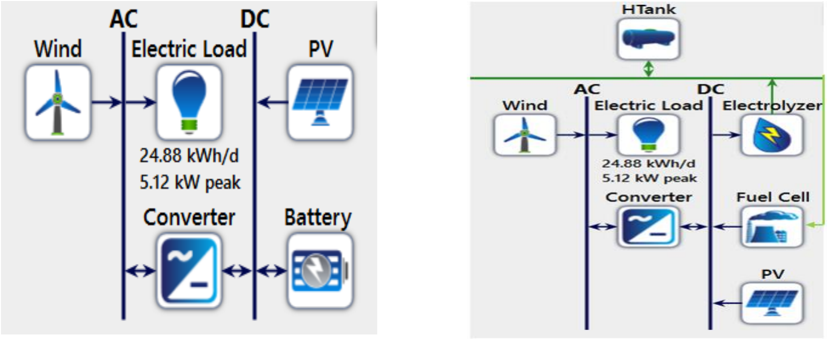


Fig 4.1 Elements for designing models [Screenshots from Homer Pro Software]

- Scenario 1: Solar PV, Converter, Wind turbine, Battery Storage, Gasoline Generator
- Scenario 2: Solar PV, Converter, Battery Storage, Gasoline Generator
- Scenario 3: Wind turbine, Battery Storage, Gasoline Generator
- Scenario 4: Wind turbine, Battery Storage, Solar PV, converter
- Scenario 5: Solar PV, Wind turbine, Converter, Fuel Cell, Hydrogen Tank, Electrolyzer



Scenario 1 scenario 2 Scenario 3



Scenario 4 Scenario 5

Fig 4.2 Hybrid system composed of WT, PV, FC, and battery storage to serve AC load [Screenshots from Homer Pro Software]

The specifications of the components of the different scenario are highlighted in tables below. The data was provided by the HOMER Pro software. Tables 4.1-4.7 detail the specifications of the components of the different scenarios. The data is derived from the HOMER Pro library. The HOMER Pro library data is derived directly from industry [63].

Table 4.1 Specifications of PV system

Parameter	Value
Type	Monocrystalline Flat plate
Capital cost, $/kW	2500
Replacement, $/kW	2500

O&M, $/kW/yr	10
Lifetime, years	25
Derating factor, %	80

Table 4.2 Specifications wind turbine

Parameter	Value
Type	Horizontal axis
Capital cost, $/kW	18000
Replacement cost, $/kW	18000
O&M, $/kW/yr	360
Lifetime, years	25
Hub Height, m	17

Table 4.3 Specifications of generator

Parameter	Value
Type	Gasoline powered
Capital cost, $/kW	400
Replacement cost, $/kW	400
O&M, $/kW/yr	5
Lifetime, years	25
Gasoline fuel price, $/L	0.4

---

[1] *$ Used in this session and the sessions after it refer to US dollars.*

The derating factor is a factor applied by HOMER to account for reduced PV array output arising from real-world operating conditions like dust covering the panels, wiring losses and many others.

Table 4.4 Specifications of battery

Parameter	Value
Type	Lead-Acid
Capital cost, \$/kW	300
Replacement cost, \$/kW	240
O&M, \$/kW/yr	10
Lifetime, years	10
Round trip efficiency, %	80

Table 4.5 Specifications of fuel cell

Parameter	Value
Type	PEM
Capital cost, \$/kW	3000
Replacement cost, \$/kW	2700
O&M, \$/KW/yr	0.020
Lifetime, years	4.6

Table 4.6 Specifications of Electrolyzer

Parameter	Value
Type	PEM
Capital cost, \$/KW	1200
Replacement cost, \$/KW	1000
O&M, \$/KW/yr	0.30
Efficiency, %	85
Lifetime, years	15

Table 4.7 Specifications of Hydrogen tank

Parameter	Value
Capital cost, \$/Kg H_2	1000

Replacement cost, $/KW	1000
O&M, $/KW/yr	0.30
Lifetime, years	25

4.2. Simulation and optimization

During the simulation, the performance of the different scenarios is modeled on an hourly basis all-round the year to determine the feasibility and Net present cost. NPC is used to equate the cost of the system over a period (lifetime) to the present cost. During the optimization process, HOMER Pro runs several simulations of different combinations of the components of the system in other obtain the combination that satisfies the load requirements at the lowest net present cost. HOMER will obtain the most optimal mix at different input assumptions such as nominal discount rate, average wind speed or fuel price. These inputs are in most cases beyond the control of the model designer This allows the model designer gauge the effects of uncertainty in the model inputs [65].

4.3. Control strategy

HOMER Pro models two types of control strategy; load following LF and cycle charging CC. Cycle charging is a type of dispatch strategy where the load requirement is met primarily by a generator operating at full capacity when a generator is in use and only surplus electrical production is channeled to meet lower priority objectives like meeting the deferrable load, power bank charging, and serving the electrolyzer. In the load following strategy, whenever a generator set is in use it only produces enough power to meet the load requirements. Other objectives like power bank charging and meeting the deferrable load are served by renewable sources. In cases where there is grid connection, the generating set can still be ramped up to sell to the grid if it is economically viable.

4.4. Mathematical formulation of the problem

HOMER Pro’s objective function is to minimize the Net Present Cost (NPC). This study was carried out bearing in mind the following assumptions: Nominal discount rate of 10%, lifetime of 25 years, inflation rate per annum of 2%, and simulation time step of one hour. The nominal discount rate is the rate at which money can be borrowed while the inflation rate is the rate at which prices rise over overtime. HOMER calculates the annual real discount rate using the nominal discount rate and inflation rate as seen in equation 4.1 [66]. Where x is annual real discount rate, i^i is nominal discount rate and f is inflation rate.

$$x = \frac{i' - f}{1 + f} \tag{4.1}$$

Equation 4.2 [66] is the formula HOMER Pro uses to calculate the cost associated with each component of a system.

$$C_{ann,i} = C_{capital,i} + C_{o\&m,i} + C_{replacement,i} + C_{fuel,i} \tag{4.2}$$

Where $C_{ann,i}$ is the annualized cost, $C_{capital,i}$ is the capital cost, $C_{O\&M,i}$ is the operation and maintenance cost cost, $C_{replacement,i}$ is the replacement cost , and $C_{fuel,i}$ is the fuel cost. The annualized cost of all components are summed up including costs associated with pollution penalties to obtain the total annualized cost $C_{ann,tot}$. The total annualized cost is used in calculating the NPC as seen in equation 4.3 [66].

$$C_{\mathrm{NPC}} = \frac{C_{\mathrm{ann,tot}}}{CRF(x, R_{\mathrm{proj}})}, \tag{4.3}$$

Where, x is the annual real discount rate, R_{proj} is the project lifetime, and CRF is the capital recovery factor and can be calculated by the equation 4.4 [66]

$$CRF(x, R_{proj}) = \frac{x(1+x)^{R_{proj}}}{(1+x)^{R_{proj}} - 1} \tag{4.4}$$

4.5. Object and load description

The Residential building for which the hybrid installation will be designed is a fully detached bungalow located in Warri, Delta State Nigeria (5º33.3N 5º47.6 E). It comprises 4 rooms, a living and dining area and has an area of 309.67 m^2. The building is connected to the grid. However, power supply is erratic, and it relies almost entirely on gasoline generator to meet its electricity. All heating and cooling demands are also met by electrical appliances and as such are included in the total electric demand. Fig 4.4 shows the view of the building.

Fig 4.4 View of the residential building for which hybrid system is to be installed

The annual electric demand for building is 9079.80 kWh. Table 4.8 shows the load specification.

Table 4.8 Load Specification

Electric load	Value
Average [kW/day]	24.88
Average [kW]	1.04
Average [KWh/year]	9079.80

The load is determined by summing up the ratings of all appliances used and multiplied by the number of hours used. The obtained results are entered into HOMER as load data and HOMER simulates the load profile. Fig 4.5 and 4.6 shows the seasonal load profile January records the highest electrical demand (2.23kW). June records the lowest electrical demand (1.35kW).

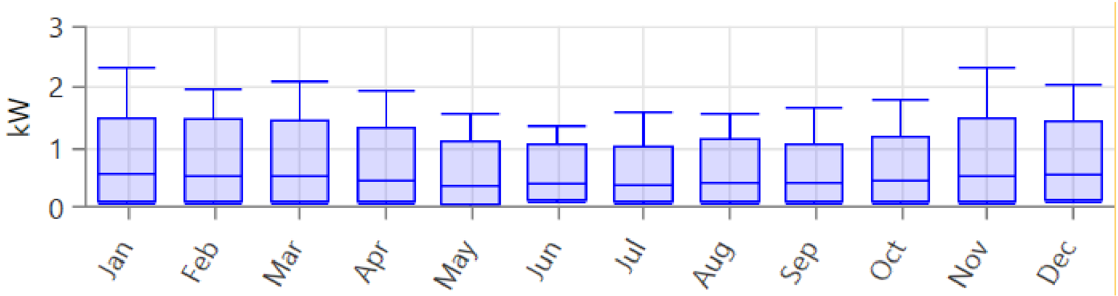


Fig. 4.5 Seasonal profile [Screenshots from Homer Pro Software]

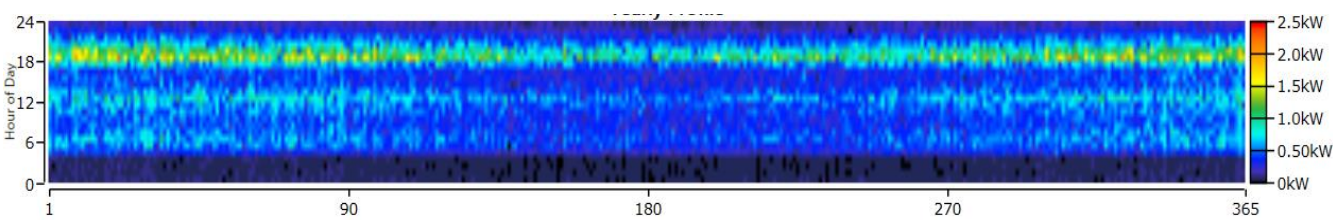


Fig 4.6 Yearly load profile [Screenshots from Homer Pro Software]

4.6. Meteorological data

Meteorological data relevant to this study are the hourly solar radiation, wind speed, and the monthly average temperature. They have been derived from NASA Surface meteorology and Solar Energy database [63]. Fig. 4.7 shows the monthly variations in solar radiation. This fluctuation affects the PV component's output. The average solar radiation in the place where the residential building is located is about 4.53 kWh/m^2. The peak solar radiation occurs in January-February (5.33 kWh/m^2) and the minimum in July (3.30 kWh/m^2). Other factors like the sky clearness index, dust and debris, and relative position of the sun can also affect the PV output.

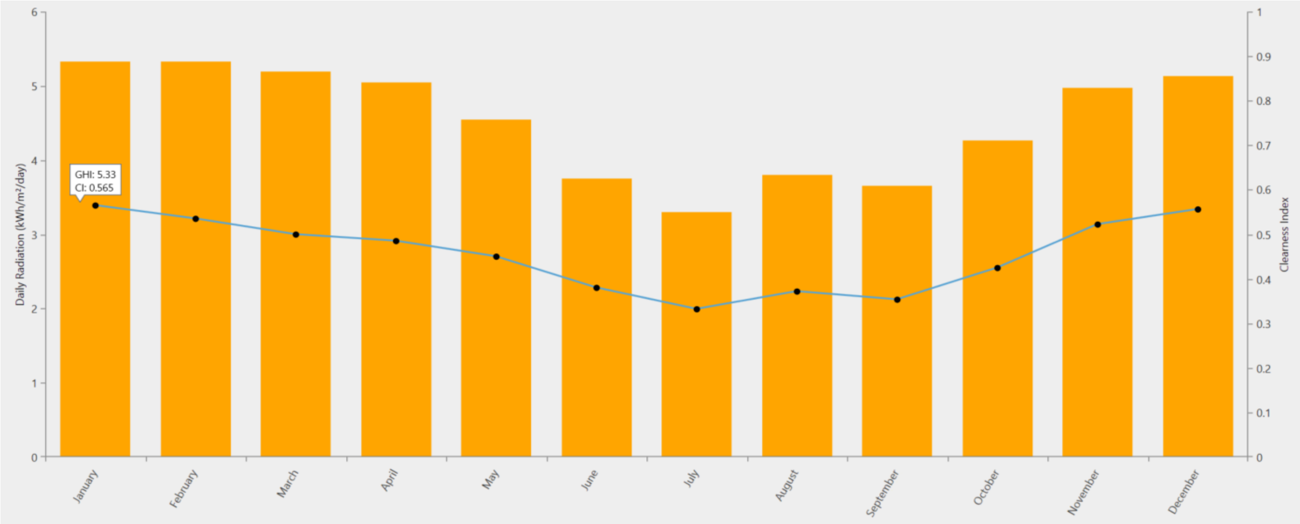


Fig 4.7 Monthly average solar radiation and clearness index [63]

Fig 4.8 shows the average monthly wind speed variation. The wind speed is maximum in August (3.68 m/s) and minimum in May (2.53 m/s). The data is obtained from NASA Surface metrology and Solar Energy database measured at 50m above sea level [63]. The wind speed influences the wind turbine output.

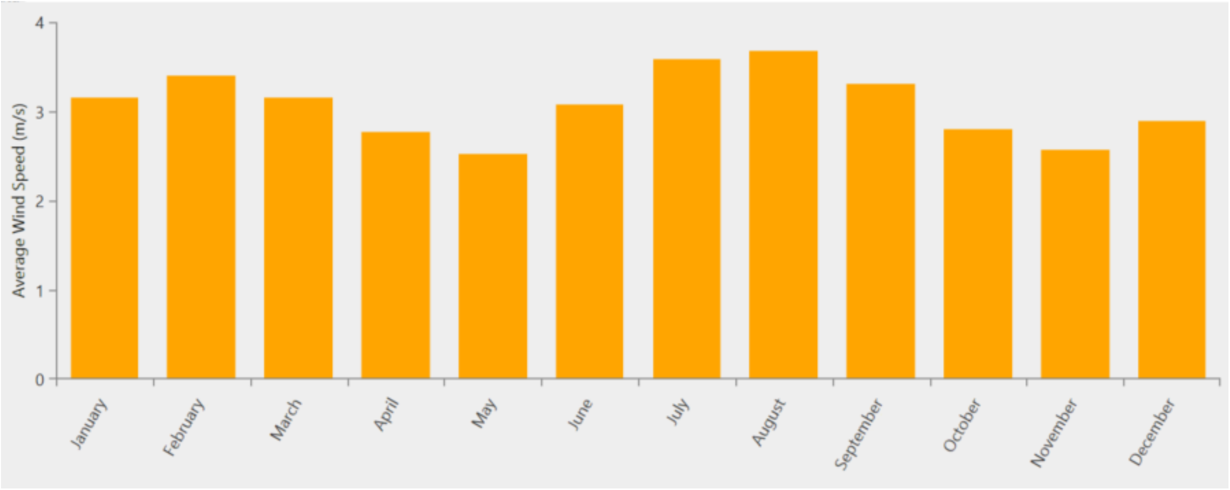


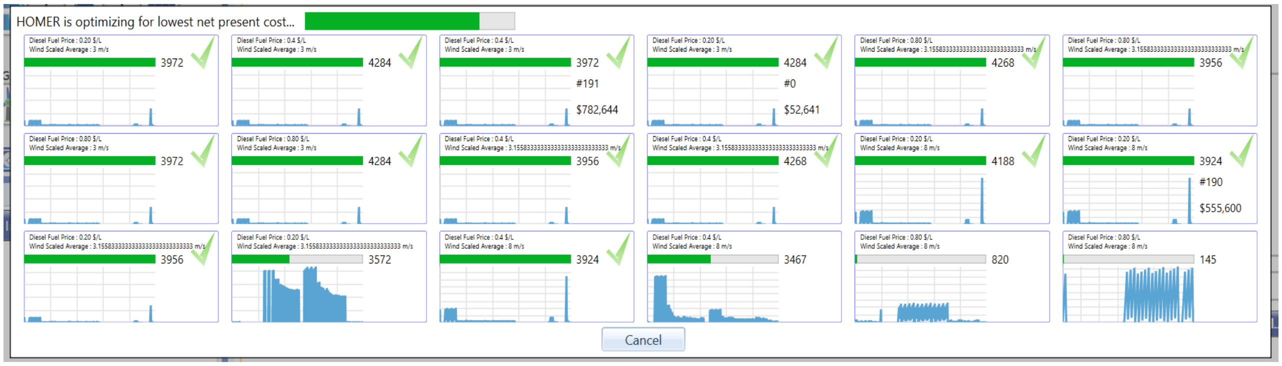
Fig 4.8 Monthly average wind speed [63]

Average temperature variation can affect electric demand and PV output. When the temperature is high there will be increased need for air conditioning. This will result in increased electrical demand. Fig. 4.9 shows the monthly average temperature in the location. The coolest month is July (29ºC) and the warmest month is January (33.5ºC).

Fig. 4.9 Monthly average temperature [63]

Chapter 5. Simulation and results

The simulation and optimization results of the scenarios are presented in this chapter. The simulation of the operation of the systems is done by making energy balance calculations for each of the 8,760 hours in a year. For every hour, HOMER compares the electric load to the amount of energy that the system can supply in that hour. For systems that include storage, HOMER decides when to charge or discharge the storage devices. For systems that meet the load requirements for the entire year, HOMER estimates the NPC considering the capital, fuel, replacement, operation, and maintenance cost. After the simulation is completed, HOMER displays a list of feasible systems. The list is sorted by the NPC. HOMER also calculates the emissions from the systems. An illustration of HOMER Pro optimizing for the lowest present cost is shown in Fig 5.1.



HOMER is optimizing for lowest net present cost...

Diesel Fuel Price : 0.20 $/L
Wind Scaled Average : 3 m/s
3972

Diesel Fuel Price : 0.4 $/L
Wind Scaled Average : 3 m/s
4284

Diesel Fuel Price : 0.4 $/L
Wind Scaled Average : 3 m/s
3972
#191
$782,644

Diesel Fuel Price : 0.20 $/L
Wind Scaled Average : 3 m/s
4284
#0
$52,641

Diesel Fuel Price : 0.80 $/L
Wind Scaled Average : 3.15583333333333333333333333 m/s
4268

Diesel Fuel Price : 0.80 $/L
Wind Scaled Average : 3.15583333333333333333333333 m/s
3956

Diesel Fuel Price : 0.80 $/L
Wind Scaled Average : 3 m/s
3972

Diesel Fuel Price : 0.80 $/L
Wind Scaled Average : 3 m/s
4284

Diesel Fuel Price : 0.4 $/L
Wind Scaled Average : 3.15583333333333333333333333 m/s
3956

Diesel Fuel Price : 0.4 $/L
Wind Scaled Average : 3.15583333333333333333333333 m/s
4268

Diesel Fuel Price : 0.20 $/L
Wind Scaled Average : 8 m/s
4188

Diesel Fuel Price : 0.20 $/L
Wind Scaled Average : 8 m/s
3924
#190
$555,600

Diesel Fuel Price : 0.20 $/L
Wind Scaled Average : 3.15583333333333333333333333 m/s
3956

Diesel Fuel Price : 0.20 $/L
Wind Scaled Average : 3.15583333333333333333333333 m/s
3572

Diesel Fuel Price : 0.4 $/L
Wind Scaled Average : 8 m/s
3924

Diesel Fuel Price : 0.4 $/L
Wind Scaled Average : 8 m/s
3467

Diesel Fuel Price : 0.80 $/L
Wind Scaled Average : 8 m/s
820

Diesel Fuel Price : 0.80 $/L
Wind Scaled Average : 8 m/s
145

Fig 5.1 HOMER Pro optimizing for lowest present cost [Screenshots from Homer Pro Software]

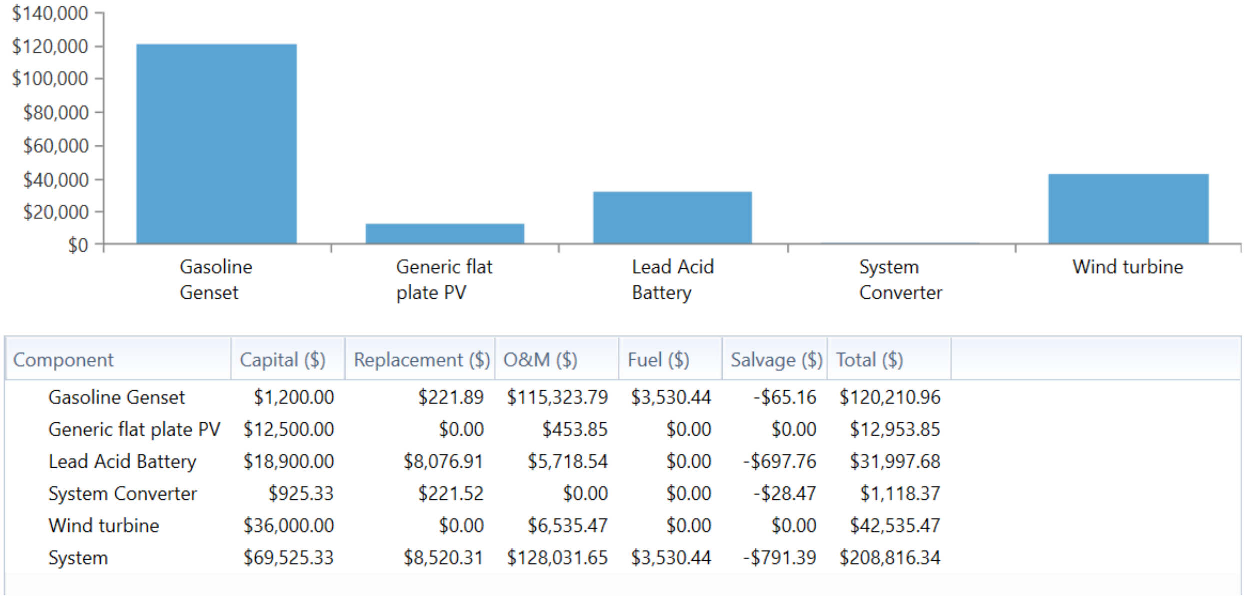
Scenario 1:

This scenario utilizes power from wind, solar and a generating set. Storage is provided by the lead acid battery. The Optimization results for this scenario are displayed in table 5.1. HOMER Pro chooses a 5kW solar installation alongside 6kW wind turbines and 63 lead acid batteries as the optimal mix to satisfy the load requirements. The configuration uses a cycle charging dispatch strategy. The generating set capacity is fixed at 3kW because this generating already exists at the location. The details of the net present cost of each component are highlighted in Fig 5.2.

The costliest component is the generating set which costs $120,210.96. The least costly component is the converter with net present cost of $1,118.37. The net present cost of the entire system is $208,816 and the startup cost is $69,525.

Table 5.1 Optimal size and cost of scenario 1

Architecture						**cost**		
Solar PV (kW)	Wind (kW)	Gen (kW)	Battery	Converter (kW)	Dispatch	NPC $	O & M $/Year	Initial Capital ($)
5	6	3	63	3.08	CC	208,816	15,345	69,525



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Gasoline Genset	$1,200.00	$221.89	$115,323.79	$3,530.44	-$65.16	$120,210.96
Generic flat plate PV	$12,500.00	$0.00	$453.85	$0.00	$0.00	$12,953.85
Lead Acid Battery	$18,900.00	$8,076.91	$5,718.54	$0.00	-$697.76	$31,997.68
System Converter	$925.33	$221.52	$0.00	$0.00	-$28.47	$1,118.37
Wind turbine	$36,000.00	$0.00	$6,535.47	$0.00	$0.00	$42,535.47
System	$69,525.33	$8,520.31	$128,031.65	$3,530.44	-$791.39	$208,816.34

Fig 5.2 Cost (NPC) Summary of scenario 1

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[2] *HOMER Pro is an American software and as such commas (,) in the displayed results are used to separate groups of thousands while period (.) is used to indicate the decimal place.*

The details of electricity production and consumption is highlighted in table 5.2. Scenario 1 satisfies the load requirements with an excess of 384 kWh/yr. 76% of the electricity generated is from renewable sources. Fig 5.3 illustrates the monthly electric production from the different sources.

Table 5.2 Electric load Production and Consumption of scenario 1

Production			Consumption		
Component	kWh/yr	%	Type	kWh/yr	%
Solar PV	6,659	61.1	AC load	9,081	100
Gasoline Gen	2,539	23.3	DC load	-	-
Wind	1,696	15.6	Deferrable	-	-
Total	10,893	100	Total	9,081	100

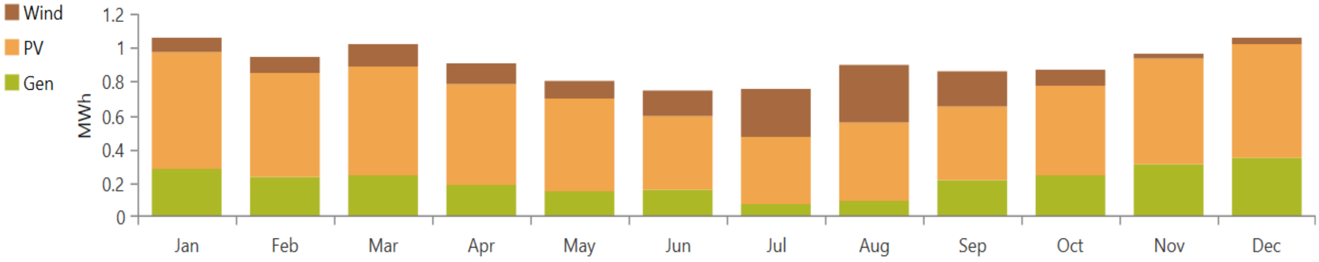
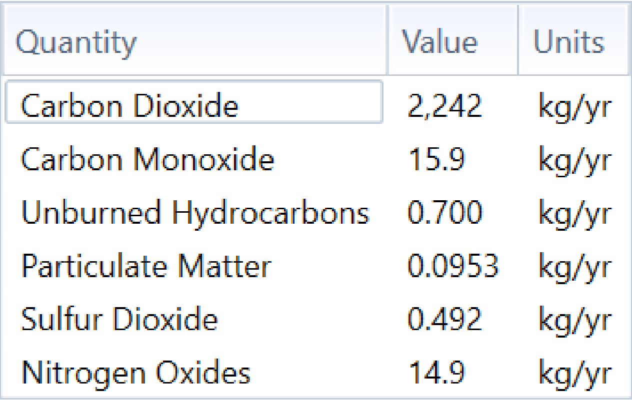


Fig 5.3 Monthly Electric production of Scenario 1

The emissions produced every year by scenario 1 are shown in fig 5.4. The emissions are produced from burning fuel in the generator.



Quantity	Value	Units
Carbon Dioxide	2,242	kg/yr
Carbon Monoxide	15.9	kg/yr
Unburned Hydrocarbons	0.700	kg/yr
Particulate Matter	0.0953	kg/yr
Sulfur Dioxide	0.492	kg/yr
Nitrogen Oxides	14.9	kg/yr

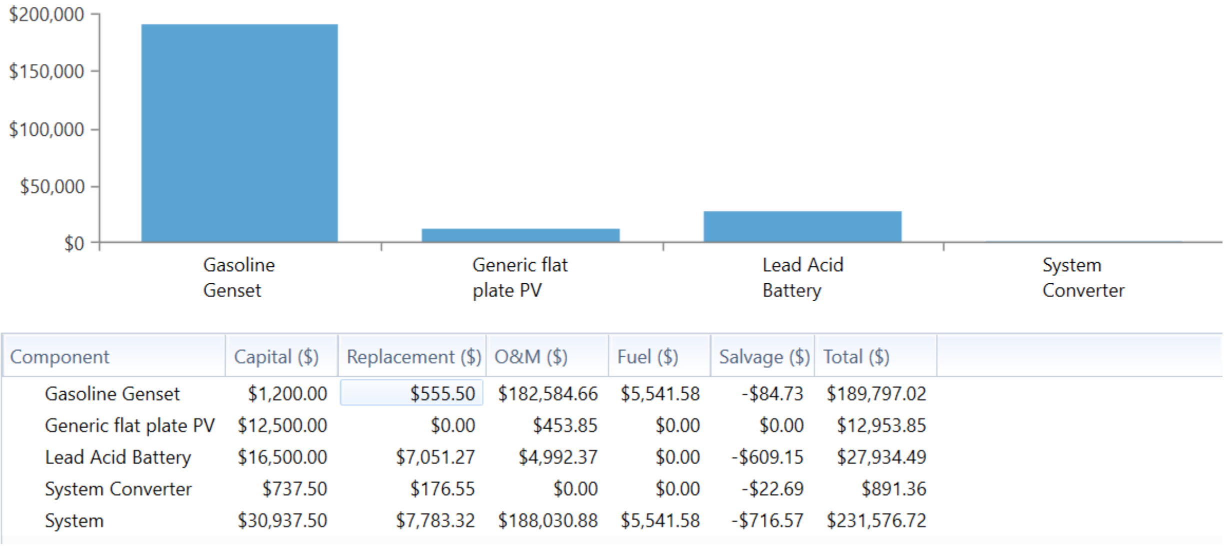
Fig 5.4 Emissions of scenario 1

Scenario 2:

This scenario utilizes power from solar and a generating set. lead acid batteries store energy for better load balancing. The optimal size from the simulation is a 5kW solar PV array alongside the 3kW generating set. Table 5.3 shows the results of the simulation. The net present cost summary in US dollars of the components of this scenario is illustrated in fig 5.5. The costliest component is the generating set which costs $189,797.02. The least costly component is the converter with net present cost of $737.50. The system uses are cycle charging dispatch strategy.

Table 5.3 Optimal size and cost of scenario 2

Architecture						Cost		
Solar PV (kW)	Wind (kW)	Gen (kW)	Battery	Convert-er (KW)	Dispatch	NPC $	O & M $/Year	Initial Capital ($)
5	-	3	55	2.46	CC	231,577	22,104	30,938



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Gasoline Genset	$1,200.00	$555.50	$182,584.66	$5,541.58	-$84.73	$189,797.02
Generic flat plate PV	$12,500.00	$0.00	$453.85	$0.00	$0.00	$12,953.85
Lead Acid Battery	$16,500.00	$7,051.27	$4,992.37	$0.00	-$609.15	$27,934.49
System Converter	$737.50	$176.55	$0.00	$0.00	-$22.69	$891.36
System	$30,937.50	$7,783.32	$188,030.88	$5,541.58	-$716.57	$231,576.72

Fig 5.5 Net Present cost of components of scenario 2

Table 5.4 details the electricity production and consumption of the system. Scenario 2 meets the load requirements and produces an excess of 157 KWh/yr. The renewable fraction is 62%. The monthly electric production from the different power sources is shown in Fig 5.6. The yearly emission from the system is shown in fig 5.7

Table 5.4 Electric load Production and Consumption of scenario 2

Production			Consumption		
Component	KWh/yr	%	Type	KWh/yr	%
Solar PV	6,659	62.6	AC load	9,081	100
Gasoline Gen	3,981	37.4	DC load	-	-
Wind	-	-	Deferrable	-	-
Total	10,641	100	Total	9,081	100

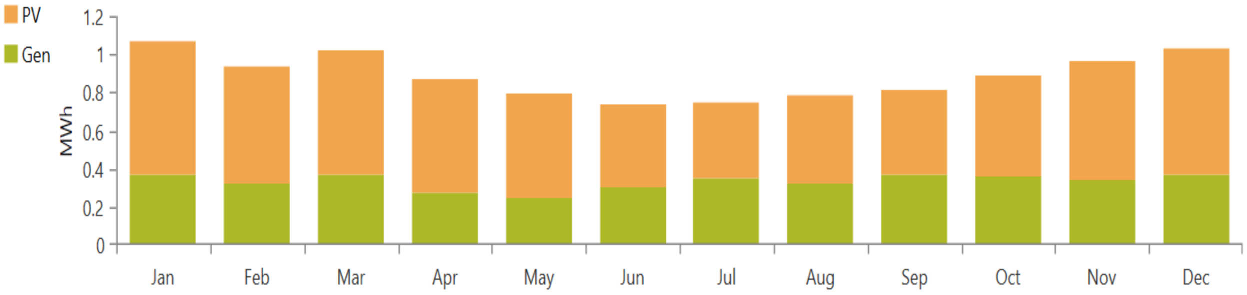
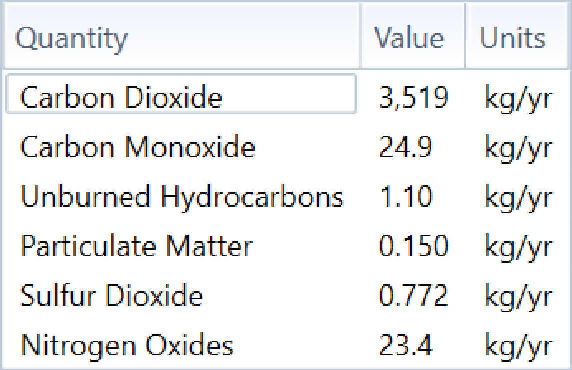


Fig 5.6 Monthly Electric production of Scenario 2



Quantity	Value	Units
Carbon Dioxide	3,519	kg/yr
Carbon Monoxide	24.9	kg/yr
Unburned Hydrocarbons	1.10	kg/yr
Particulate Matter	0.150	kg/yr
Sulfur Dioxide	0.772	kg/yr
Nitrogen Oxides	23.4	kg/yr

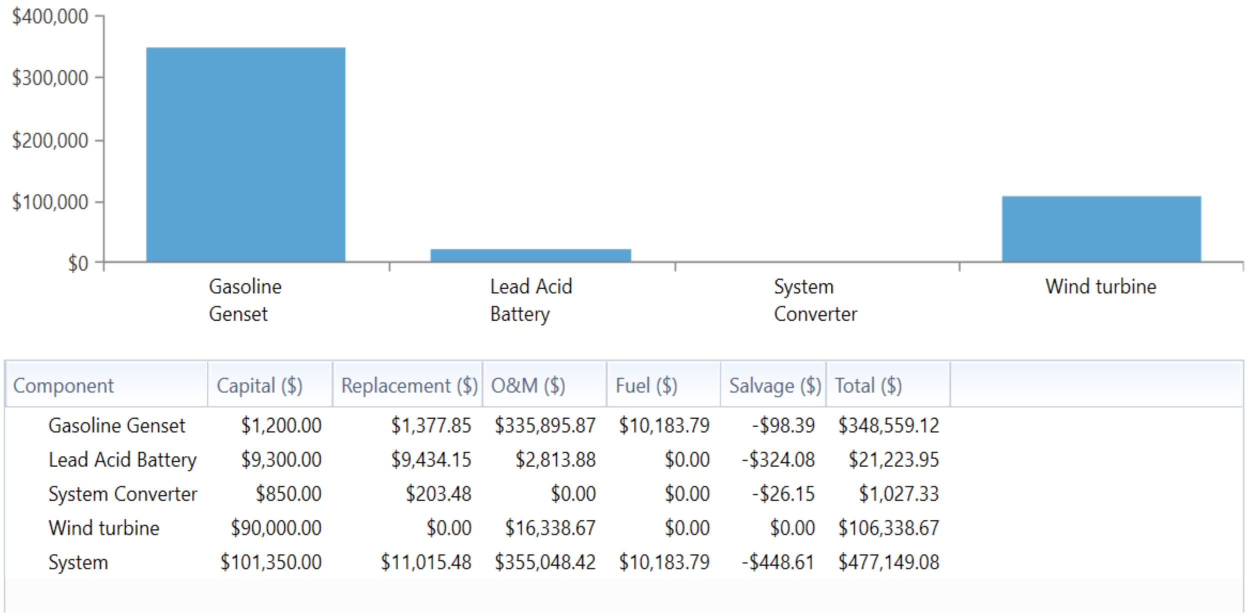
Fig 5.7 Emissions of scenario 2

Scenario 3:

This scenario is a hybrid system composed of a generating set and wind turbines. HOMER found the optimal sizes to satisfy the load requirements to be 15 kW wind turbine alongside the 3kW generating set. The simulation results are shown in Table 5.5. The net present cost of the system in US dollars is $477,149. It cost a total of $101,350 to install. The summary of net present cost of the components of the system are highlighted in Fig 5.8.

Table 5.5 Optimal size and net present cost of scenario 3

Architecture						Cost		
Solar PV (kW)	Wind (kW)	Gen (kW)	Battery	Convert-er (kW)	Dispatch	NPC $	O & M $/Year	Initial Capital ($)
-	15	3	31	2.83	CC	477,149	41,401	101,350



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Gasoline Genset	$1,200.00	$1,377.85	$335,895.87	$10,183.79	-$98.39	$348,559.12
Lead Acid Battery	$9,300.00	$9,434.15	$2,813.88	$0.00	-$324.08	$21,223.95
System Converter	$850.00	$203.48	$0.00	$0.00	-$26.15	$1,027.33
Wind turbine	$90,000.00	$0.00	$16,338.67	$0.00	$0.00	$106,338.67
System	$101,350.00	$11,015.48	$355,048.42	$10,183.79	-$448.61	$477,149.08

Fig 5.8 Net Present Cost Summary of Scenario 3

Details of the electricity production from this system are shown in Table 5.6. The system satisfies the electric load with an excess production of 1,012 kWh/yr. It has a renewable fraction of 36%. Due to insufficient windspeed, the generating set supplies more of the electric load about 63% in contrast to scenario 1 and 2. The monthly electricity production is depicted in Fig 5.9 while the emission is shown in Fig 5.10.

Table 5.6 Electric load Production and Consumption of scenario 3

Production			Consumption		
Component	kWh/Yr	%	Type	kWh/Yr	%
Solar PV	-	-	AC load	9,080	100
Gasoline Gen	7,316	63.3	DC load	-	-
Wind	4,239	36.7	Deferrable	-	-
Total	11,555	100	Total	9,080	100

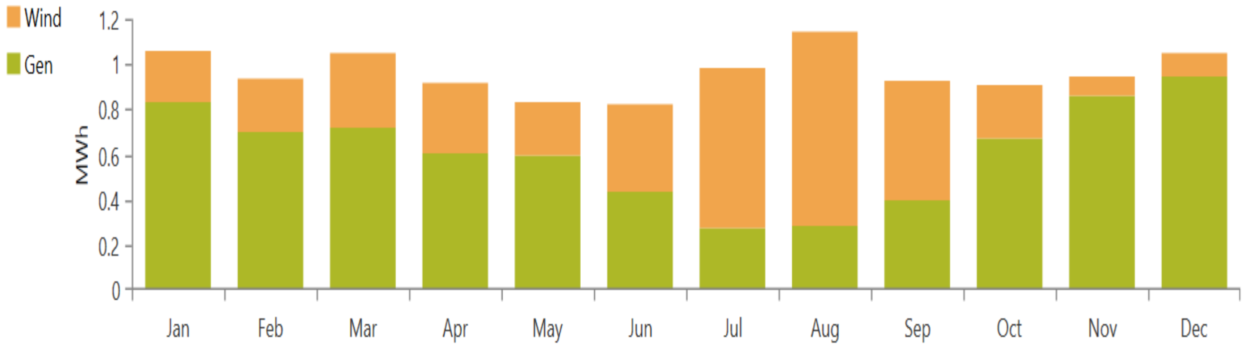
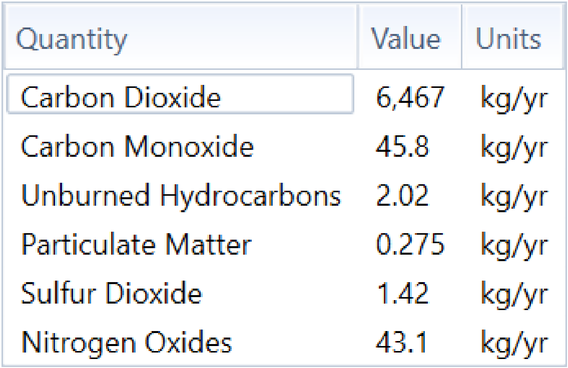


Fig 5.9 Monthly Electricity production from scenario 3



Quantity	Value	Units
Carbon Dioxide	6,467	kg/yr
Carbon Monoxide	45.8	kg/yr
Unburned Hydrocarbons	2.02	kg/yr
Particulate Matter	0.275	kg/yr
Sulfur Dioxide	1.42	kg/yr
Nitrogen Oxides	43.1	kg/yr

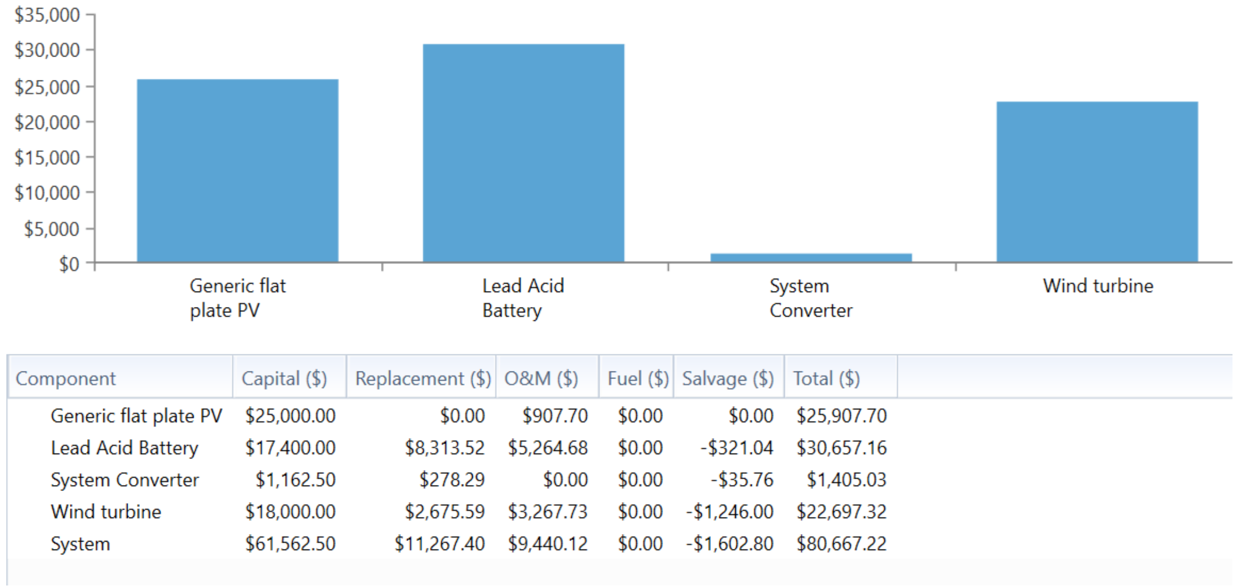
Fig 5.10 Emissions from Scenario 3

Scenario 4:

Scenario 4 was designed to have the load requirement met entirely by renewable sources. HOMER chooses 10kW of solar PV, 3kW wind and 58 lead acid batteries as the optimal sizes to satisfy the load. The results are shown in Table 5.7. The system's net present cost in US dollars is $80,667. The dispatch strategy is cycle charging. It cost $25,000 to install. The details of the net present cost of the components of this system are shown in Fig 5.11. In this scenario the costliest component is the battery storage ($30,657.16) and the least costly is the system converter ($1,405.03). Because the system is completely renewable there are no emissions from this system Fig 5.13.

Table 5.7 Optimal size and net present cost of scenario 4

Architecture						cost		
Solar PV (kW)	Wind (kW)	Gen (KW)	Battery	Convert-er (kW)	Dispatch	NPC $	O & M $/Year	Initial Capital ($)
10	3	-	58	3.88	CC	80,667	2,105	25,000



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic flat plate PV	$25,000.00	$0.00	$907.70	$0.00	$0.00	$25,907.70
Lead Acid Battery	$17,400.00	$8,313.52	$5,264.68	$0.00	-$321.04	$30,657.16
System Converter	$1,162.50	$278.29	$0.00	$0.00	-$35.76	$1,405.03
Wind turbine	$18,000.00	$2,675.59	$3,267.73	$0.00	-$1,246.00	$22,697.32
System	$61,562.50	$11,267.40	$9,440.12	$0.00	-$1,602.80	$80,667.22

Fig 5.11 Net Present Cost Summary of Scenario 4

The details of the electric production and consumption are shown in Table 5.8. The configuration meets the load requirements with an excess of 3850 KWh/yr. The excess production can be sold to the grid. The system has a 100% renewable fraction. The monthly electricity production is shown in Fig 5.12

Table 5.8 Electric load Production and Consumption of scenario 4

Production			Consumption		
Component	KWh/yr	%	Type	KWh/yr	%
Solar PV	13,319	94	AC load	8,782	100
Gasoline Gen	-	-	DC load	-	-
Wind	848	6	Deferrable	-	-
Total	14,166	100	Total	8,782	100

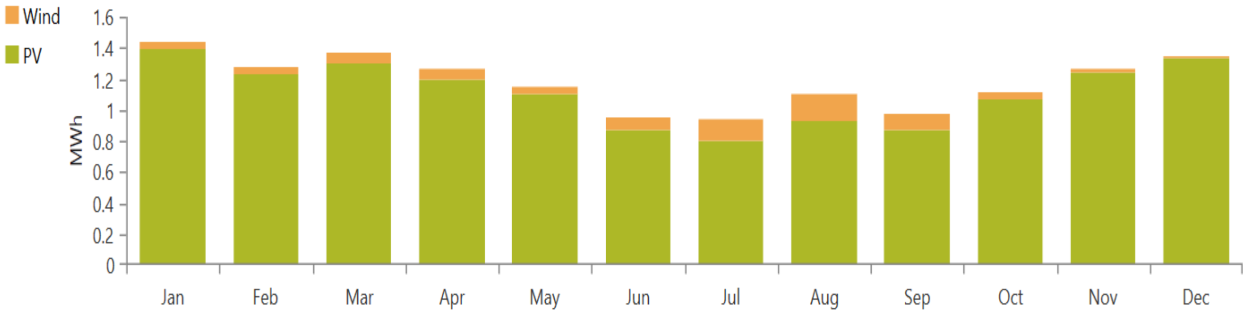
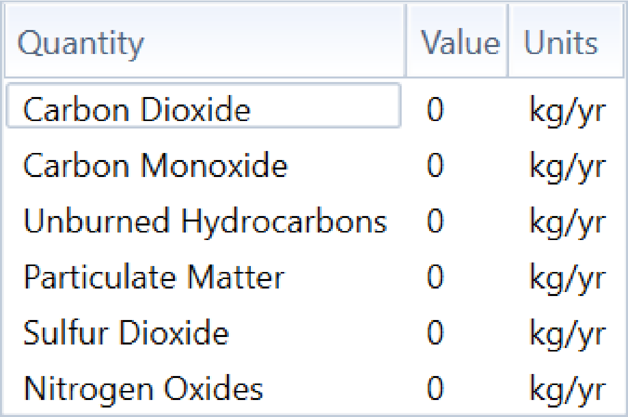


Fig 5.12 Monthly Electricity production from scenario 4



Quantity	Value	Units
Carbon Dioxide	0	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	0	kg/yr

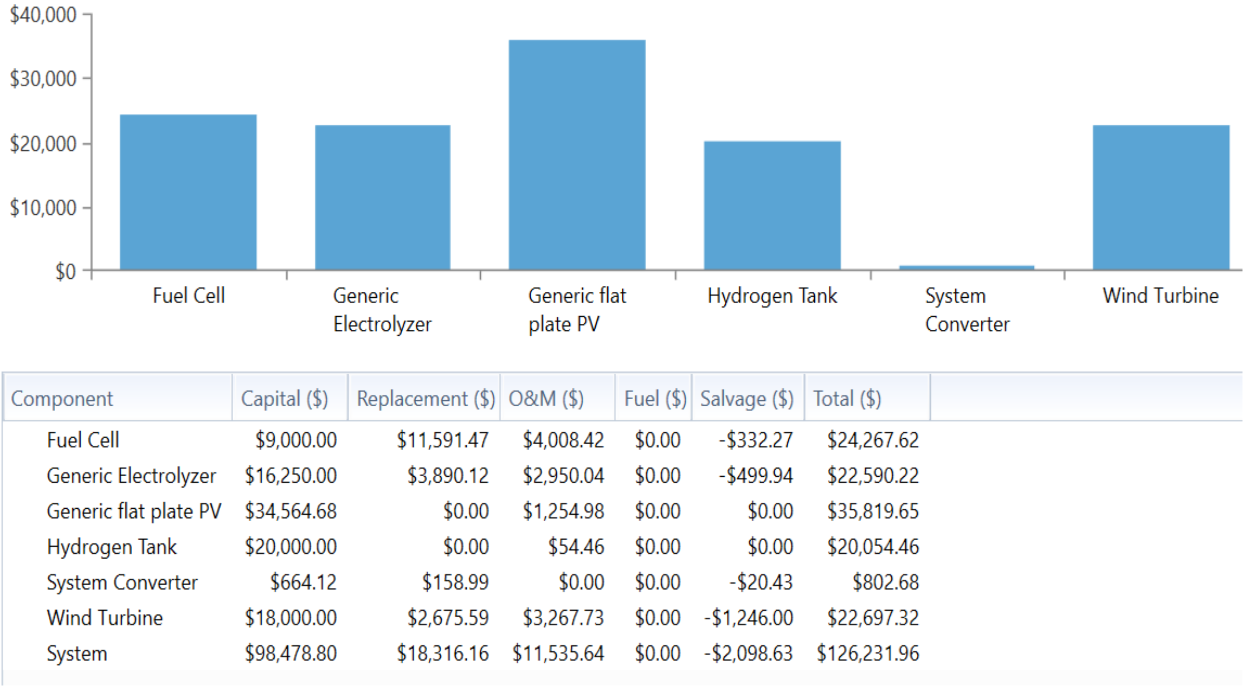
Fig 5.13 Emissions from Scenario 4

Scenario 5:

In this scenario power is also generated solely from renewable sources. The system uses the excess renewable electricity to produce hydrogen which is stored in a tank and used by the fuel cell to produce electricity later. The result of the optimization is shown in Table 5.9. It consists of a 13kW solar PV array, 3kW wind turbine, 6.5kW electrolyzer, a 20Kg hydrogen tank, a 1.5kW converter and a cycle charging strategy. The initial capital for installation in US dollars is $98,479 and the net present cost is $126,232. The costliest component of this system is the PV array costing $35,819.65. The least costly component is the $802.68. The net present cost summary of the entire system is illustrated in figure 5.14.

Table 5.9 Optimal size and net present cost of scenario 5

Architecture							Cost		
Solar PV (kW)	Wind (kW)	FC (KW)	Electrolyzer (KW)	H Tank (Kg)	Dispatch	Convert-er (KW)	NPC $	O & M $/year	Initial Capital ($)
13.8	3	3	6.5	20	CC	1.50	126,232	3,058	98,479



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Fuel Cell	$9,000.00	$11,591.47	$4,008.42	$0.00	-$332.27	$24,267.62
Generic Electrolyzer	$16,250.00	$3,890.12	$2,950.04	$0.00	-$499.94	$22,590.22
Generic flat plate PV	$34,564.68	$0.00	$1,254.98	$0.00	$0.00	$35,819.65
Hydrogen Tank	$20,000.00	$0.00	$54.46	$0.00	$0.00	$20,054.46
System Converter	$664.12	$158.99	$0.00	$0.00	-$20.43	$802.68
Wind Turbine	$18,000.00	$2,675.59	$3,267.73	$0.00	-$1,246.00	$22,697.32
System	$98,478.80	$18,316.16	$11,535.64	$0.00	-$2,098.63	$126,231.96

Fig 5.14 Net Present Cost Summary of Scenario 5

The results of the simulations indicates that there was an excess production of 1,654 KWh/yr. The load is met 100% by renewable resources. The monthly electric production is shown in Fig 5.15. The system produces a total of 277Kg of hydrogen annually. The fuel cell utilizes 267Kg of this hydrogen to produce electricity. The monthly hydrogen production from the electrolyzer is shown in Fig 5.16. The emission from this scenario is detailed in Fig 5.17

Table 6.10 Electric load Production and Consumption of scenario 5

Production			Consumption		
Component	KWh/yr	%	Type	KWh/yr	%
Solar PV	18,414	77.6	AC load	8,794	40.6
Fuel Cell	4,454	18.8	DC load	-	-
Wind	848	3.57	Electrolyzer	12,843	-
Total	23,716	100	Total	21,637	59.4

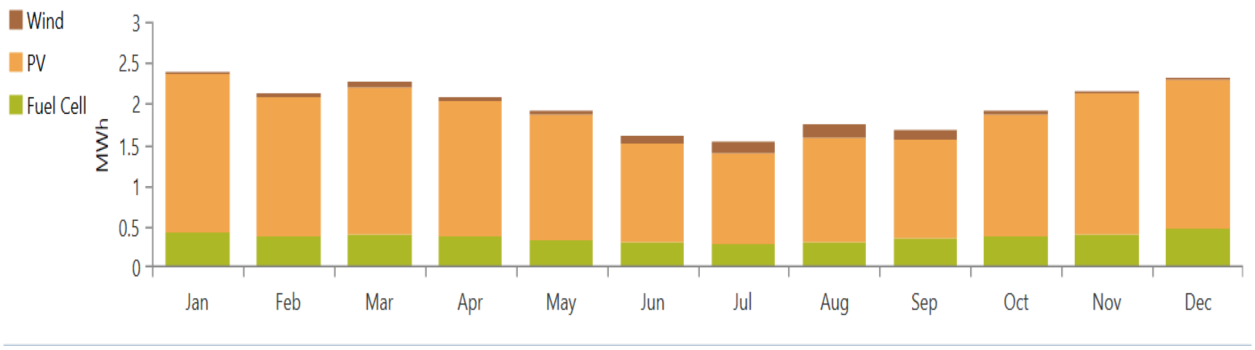


Fig 5.15 Monthly Electricity production from scenario 5

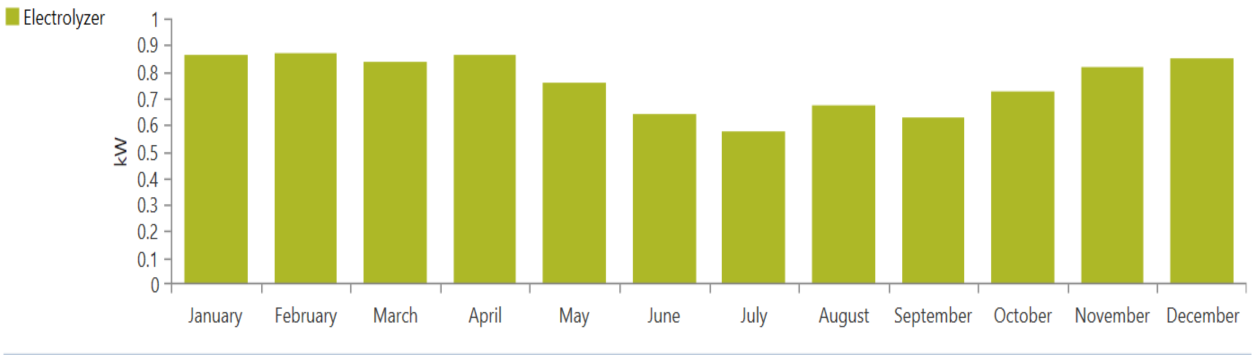
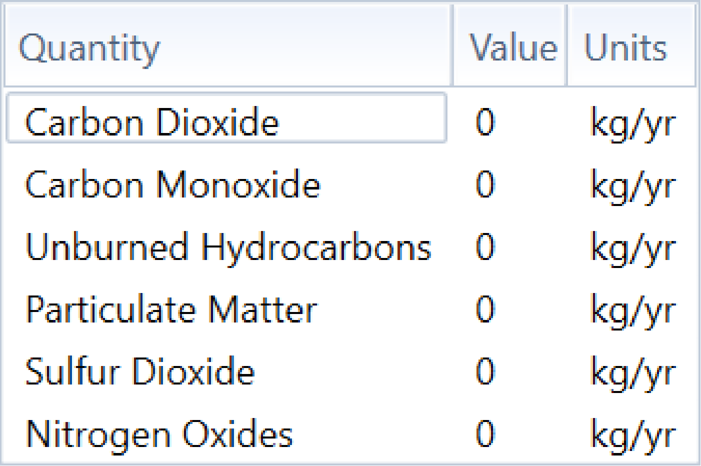


Fig 5.16 Monthly Hydrogen Production from scenario 5



Quantity	Value	Units
Carbon Dioxide	0	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	0	kg/yr

Fig 5.17 Emissions from scenario 5

Fig 5.18 and Fig 5.19 illustrates cost and emission comparison of all scenarios. Scenario 4 is the winning scenario because it has the least net present cost and produces no emission. Although the base scenario has the least installation cost the, the high net present cost and amount of emission produced makes it the least desirable. The results from scenario 3 suggest that wind turbines may not be ideal for that location. The wind speed was not sufficient to produce enough electricity to satisfy the load requirements. Although the wind capacity installed was 3 times more than the solar capacity in scenario 2, the system still relied more on the generating set.

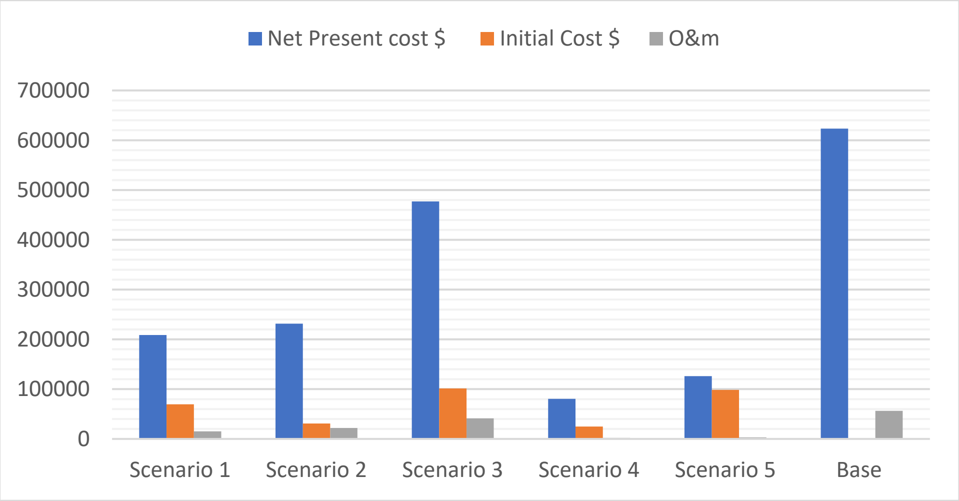


Fig 5.18 Economic comparison of all scenarios

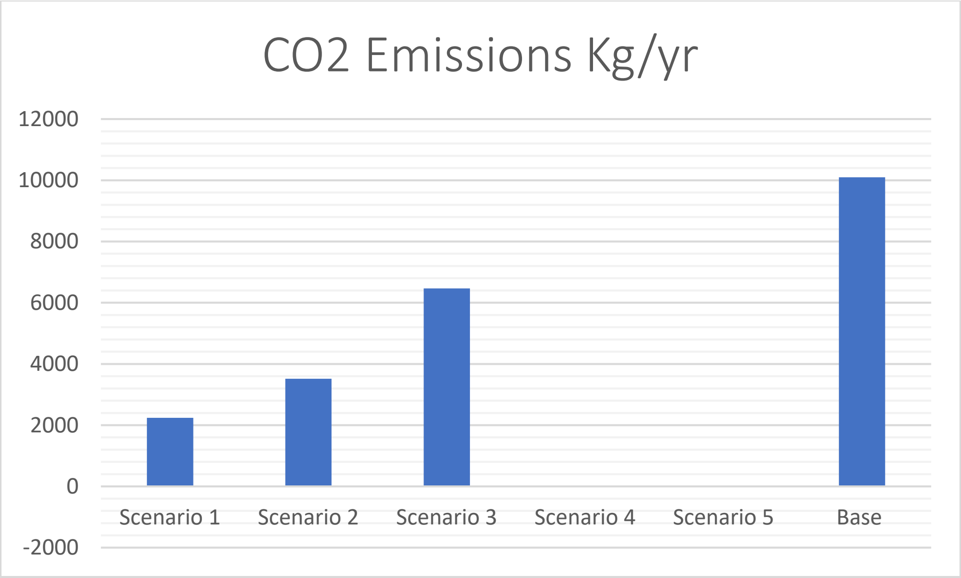


Fig 5.19 Emission comparison of all scenarios

Chapter 6. Conclusion

In this study, a set of hybrid power systems for a residential building based on renewable sources and a gasoline generator were modeled and simulated. The following conclusions can be drawn based on the obtained results. The load requirements of the building can be met by all scenarios without shortages. Generating electricity from hybrid systems offer cost saving benefits. Wind installations are not ideal in the location for which the study was carried out because the installation cost is still high and the windspeed may not be sufficient to generate enough wind output to serve the load requirement. Of all studied scenarios, a hybrid power system comprising of 10kW solar and 3kW was found to be optimal. It had the least net present cost and produced no emission. Incorporating hydrogen production and storage into the power mix is very promising technology. Results from the simulation suggest that the production of hydrogen, storage, and later use to generate electricity is feasible. Asides using the produced hydrogen for electricity production, it could be used for other applications like powering hydrogen vehicles and methanol production.

6.1 Future work

In the future work, more hybrid systems consisting of biomass and geothermal resources will be considered. The scope of coverage will be extended from one residential building to the community as well. The benefits of grid-connected hybrid power systems will be evaluated as well.

Additionally, the technoeconomic benefits of including other hydrogen pathways into the power mix will be evaluated.

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